Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis

Sponsored by

United States Environmental Protection Agency

U.S. Department of Energy

Executive Summary:

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis

Modeling Climate Change Impacts and Associated Economic Damages

and

Research on Climate Change Impacts and Associated Economic Damages

June 2011

Workshop Sponsored by:

U.S. Environmental Protection Agency

U.S. Department of Energy

Workshop Report Prepared by:

ICF International

I. Introduction

In 2009 and early 2010, the U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE) joined other U.S. government agencies in conducting an analysis of the social cost of carbon (SCC). The interagency working group used the DICE, FUND, and PAGE integrated assessment models (IAM) to estimate a range of values for the SCC from 2010 to 2050 for use in U.S. government regulatory impact analyses. The U.S. government analysis concluded in February 2010 and the estimated SCC values were first used in March 2010 in the analysis of DOE's Energy Conservation Standard for Small Electric Motors. In preparation for future revisions to the U.S. government SCC analysis, EPA and DOE seek to improve the understanding of the natural scientific and economic impacts of climate change. This enhanced understanding is also intended to inform ongoing work of the U.S. government to improve regulatory assessment and policy analysis related to climate change.

To further these objectives, the EPA National Center for Environmental Economics and Climate Change Division and the DOE Office of Climate Change Policy and Technology sponsored a pair of invitational workshops on November 18-19, 2010 and January 27-28, 2011. The November workshop focused on conceptual and methodological issues related to modeling and valuing climate change impacts. It also addressed the implications of these estimates for policy analysis. The January workshop reviewed recent research on physical impacts and associated economic damages for nine impact categories (e.g., human health, agriculture, sea level), with a particular focus on knowledge that might be used to improve IAMs.

This workshop summary was prepared by ICF International on behalf of EPA and DOE. It does not represent the official position or views of the U.S. government or its agencies, including EPA and DOE, nor has it been reviewed by the workshop speakers and other participants. The potential improvements and key findings outlined below represent the perspectives of one or more participants, as expressed at the workshops and summarized by the planning committee. However, these summaries do not necessarily represent consensus views, since none was sought at these workshops. This Executive Summary is organized into six sections: Physical Impacts Assessment; Valuation of Damages; Representing Impacts and Damages in Models; Communication of Estimates; Research and Collaboration; and Specific Impacts Sectors.

II. Physical Impacts Assessment

Participants made comments and suggestions related to impacts assessment, including the following:

- **More fully incorporate uncertainty**. Natural and social scientists should attempt to more fully characterize the uncertainty in impacts assessments, including parametric, stochastic, and structural uncertainty at all stages in the modeling process. Many of the current IAM inputs and parameters represent too narrow a range of possibilities. Complex and non-linear processes at the high ends of the impacts probability distribution (i.e., "fat tails") should be better characterized.

- **Consider both top-down and bottom-up approaches.** Estimates from both top-down and bottom-up approaches can help to estimate and bound the range of climate change impacts. For bottom-up approaches, the appropriate scale and detail may be different for each sector.

- **Incorporate threshold effects of physical and biological impacts.** Mechanistic and process models relying on basic principles (e.g., conservations of energy, plant biophysiology, ocean biogeochemistry) should be used, when possible, to extrapolate responses to new conditions, since statistical methods may not capture non-linear threshold effects of unprecedented levels of change. When climate change impacts are expected to be within or close to the range of past variations, statistical models are appropriate.

- **Capture climate variables beyond global mean temperature.** A better characterization of multiple climate variables (e.g., precipitation, storms, seasonal and diurnal temperature variations, rate of temperature change) and threshold effects on a geographically disaggregated scale could improve model calibration and the accuracy of local damage projections.

- **Focus research efforts on sectors that could have the largest influence on overall damage estimates.** This will include research on impact categories that could comprise a large share of total damages but where relatively little information has been collected to date. Researchers should not simply focus on issues that are easiest to approach. Research priorities should be guided by the combination of potential consequences and uncertainty, not one or the other alone.

- **Increase focus on high-impact events, multi-century impacts.** Existing studies tend to examine the means of the impacts probability distribution, neglecting the low-probability, high impact tails of the distribution, which can have a significant influence on IAM results. Impact studies should address this gap, recognize the potential for unexpected and unpredictable events, and attempt to model very long-term impacts (e.g., beyond 2100), despite great associated uncertainty. To do this, modelers should develop more complete multi-century projections for socio-economic and climate inputs including estimates of socio-economic uncertainty.

- **Rigorously test, compare, and evaluate impact models**. Model intercomparison projects have helped to improve physical climate models and could be used to improve impact models.

III. Valuation of Damages

Comments and suggestions related to damage valuation included the following:

- **Consider alternate functional forms for damage functions.** Representation of damages could be improved by: evaluating the additive or multiplicative nature of impacts; better incorporating discontinuities; better capturing natural capital and its interactions with physical and social capital; and generally considering a broader set of functional forms. Alternate forms are particularly important given the challenges in extrapolating damage functions calibrated at 2-3°C warming to considerably higher global mean temperature increases.

- **Clearly incorporate human behavioral responses.** Adaptation and technological development should be more fully incorporated in estimates of climate change impacts, and the underlying assumptions associated with those factors should be clearly articulated.

- **Consider different ways of equity weighting when conducting social welfare analysis of climate policies.** Several workshop participants suggested considering different ways of incorporating equity weights into the SCC or IAMs more generally. For example, most IAMs use a utility function with a single parameter that controls preferences regarding intra-generational equity, inter-generational equity, and risk aversion. Future research should explore alternative functional forms that allow these effects to be disentangled.

- **Fully account for non-market impacts and non-use values.** This includes improving estimates of impacts currently included in some models (e.g., health impacts) and incorporating impacts currently missing from most models (e.g., ocean acidification, loss of cultural heritage). Revealed and stated preference estimates and benefit-transfer methods should be improved and estimated jointly to mitigate problems with each.

- **Consider "outer measures" of climate damages.** Developing a model for a highly simplified but inclusive "outer" measure of climate change damages may help provide an upper bound on SCC estimates. Current bottom-up models are "inner" measures that attempt to capture and sum the individual components of climate damages. Since it is challenging to capture all of the components and interactions between them, these models will tend toward underestimation.

IV. Representing Impacts and Damages in Models

Throughout both workshops, but especially during the first, participants made suggestions related to integrating impacts and damages in models. These comments included the following:

- **Improve both aggregated and disaggregated models while utilizing the strengths of each.** There are important roles for models across the spectrum of aggregation, as more or less aggregation may be appropriate for different applications. Model type and analysis time scale should be matched to analytical objective. Since aggregation can contribute to a bias in impact estimates, some models should be less aggregated spatially, temporally, and sectorally to more realistically represent impact mechanisms. Since disaggregated models can incorporate more realistic impact mechanisms and use empirical data to estimate model parameters, they can be used to calibrate components of more comprehensive aggregated models.

- **Incorporate more sectors.** IAMs should include a broader range of sectors. For example, no IAMs currently represent ocean acidification.

- **Incorporate interactions between sectors.** Interactions between sectors (and among climate and non-climate stressors) may be synergistic or antagonistic, additive, multiplicative, or subtractive, making cumulative impacts larger or smaller than the sum of the individual impacts. Double-counting should be avoided.

- **Use consistent scenarios.** Consistent socio-economic and climate scenarios should be used in impact and damage assessment to facilitate inter-comparison, integration, and combination of estimates.

- **Increase model flexibility to facilitate improvements.** IAMs should be (re)designed to facilitate updates to models or model components as new research develops. A more flexible or modular structure would allow components to be individually updated or replaced.

- **Conduct new empirical studies and better incorporate existing research.** IAMs need new primary impacts research from which to draw. Research needs include empirical studies on: physical impacts, monetization of damages, decision making under uncertainty, adaptation-related technological change, adaptive capacity, tipping points, and impacts beyond 2100. IAMs could also be improved by drawing more on the existing body of research.

V. Identify metrics for model validation. Metrics and methods of validation are needed to assess models and model results. Communication of Estimates

Participants, particularly at the first workshop, made comments and suggestions related to the communication of impacts and damages estimates. These comments included the following:

- **Increase transparency.** IAMs should be made more accessible and transparent, including their key assumptions, structural equations, parameter values, and underlying empirical studies.

- **Fully and clearly communicate uncertainty.** Communication should help decision makers and the public fully and clearly understand uncertainty and its implications. The full range of model outputs should be communicated and used, rather than focusing on one central value from a set of model runs.

- **Consider other metrics.** Multiple criteria, in addition to the SCC and cost-benefit analysis, should be used for climate-related regulatory analysis, including additional cost-effectiveness measures.

VI. Research and Collaboration

Comments and suggestions related to research and collaboration included the following:

- **Increase collaboration and communication between natural scientists, economists, and modelers.** Collaboration and communication should be increased between all parties involved in impacts assessment, damages valuation, and integrated assessment modeling. Impacts assessment and valuation efforts should be coordinated with existing efforts such as the National Climate Assessment and international impacts and valuation efforts. IAM data sources, damage functions, and outputs should be reviewed by relevant members of the Impacts, Adaptation, and Vulnerability (IAV) and economic valuation communities to ensure that IAMs reflect the current state of the primary literature for each of the impact categories.

- **Increase capacity to address challenges.** Additional funding and staff are needed to help address existing impacts and damages assessment challenges.

VII. Specific Impacts Sectors

The second workshop focused on the current state of research in nine impact categories. This section highlights key research findings and recommendations for future research for each of the categories.

Storms and Other Extreme Weather Events

- Fewer tropical storms are expected in the future, but average wind speeds and precipitation totals are expected to increase. The intensity of the strongest storms is expected to increase.

- Estimates in the literature for increases in cyclone property damages due to climate change range from 0.002 to 0.006% of global GDP. Increases in property damages from all extreme events (including cyclones) due to climate change under an A1B scenario, according to one study, range from $47-$100 billion (2008 dollars) per year, or 0.008-0.018% of GDP, by 2100.

- Fatalities may increase or decrease due to climate change impacts on extreme events, as deaths from tropical cyclones may decrease more than deaths from other extreme events (e.g., heat waves) increase. Tropical cyclones are expected to continue to be the dominant cause of extreme event-related damages.

Water Resources

- Water demand, supply, and management should be modeled on a river basin scale to effectively estimate climate change impacts.

- National estimates from the literature of climate change damages to water resources range from $12-$60 billion (2009 dollars) per year for the United States according to analyses in a range of studies.

- Coupling approaches that model changes using regional hydrologic models and those using regional economic models could help bridge some gaps in water resources damage estimation.

Human Health

- The majority of climate change health effects result from diarrhea, malnutrition, and malaria. The World Health Organization estimates that the costs to treat climate change-related cases of diarrhea, malnutrition, and malaria in 2030 would be $4 to $13 billion under a scenario in which CO_2 is stabilized at 750ppm by 2210. The study predicts a 3%, 10%, and 5% increase in cases of diarrhea, malnutrition, and malaria, respectively.

- Health impact valuation depends largely on mortality valuation, particularly in developing countries and particularly among children. Adjusting the value of a statistical life for income is critical for accurate valuation.

Agriculture

- Estimates in the literature project the global range of yield changes in the 2050s to be approximately -30 to +20% under a 2.3°C mean global temperature increase (relative to 1961-1990).

- Average global effects of climate change on agriculture are expected to be positive in the short term and negative in the long term. The location of the inflection points is unknown.

    - CO_2 fertilization from increasing CO_2 concentrations will benefit some plants (C_3 plants) more than others (C_4 plants). Elevated CO_2 concentrations especially benefit weeds.

- Agriculture contributes only 2-3% of U.S. GDP, but the highly inelastic nature of agricultural demand means that even a small reduction in agricultural production from climate change could result in large price changes and large welfare losses.

- Adaptation and technological change can help to mitigate the impacts of climate change on agriculture. A key challenge will be producing heat and drought tolerant plants with high yields.

Sea Level Rise

- Climate-induced sea level rise will be compounded by both natural and human-induced subsidence in many densely-populated coastal areas.

- Emissions abatement may stabilize the rate and ultimate total amount (in 100s of years) of sea level rise, but not reduce the current significant commitment to sea level rise.

- The valuation of sea level rise damages depends heavily on wetland values and adaptation.

Marine Ecosystems and Resources

- Increasing atmospheric CO_2 concentrations cause ocean CO_2 concentrations to increase, decreasing ocean pH, and decreasing saturation states for calcite and aragonite, which are used by marine animals to produce calcareous parts (e.g., shells).

- Damages from decreased mollusk harvest revenues due to a 0.1-0.2 ocean pH decrease are estimated at $1.7 to $10 billion in net present (2007) value losses through 2060. Under the A1FI scenario pH decreases of 0.1 and 0.2 are expected by approximately 2040 and 2060, respectively.

- Assessments using bio-climate envelopes, minimum realistic models, and ecosystem and food web models would be beneficial to estimate marine impacts.

- A wide variety of studies to estimate damages is needed, using both revealed and stated preferences, to estimate total economic value of marine ecosystems and resources. Analyzing the results available from multiple existing studies could be used in a benefit transfer study to estimate economic value by transferring available information into the appropriate context.

Terrestrial Ecosystems and Forestry

- Three major types of terrestrial ecosystem impacts are expected: changes in vegetation distribution and dynamics, wildfire dynamics, and species extinction risks. For example, predicted global vertebrate extinctions due to land use and climate change range from over 30% to nearly 60% for >2 degree warming.

- Understanding changes in pest outbreaks, interior wetlands, and snow pack are important gaps.

- Natural scientists and economists need to work together to identify biophysical impacts assessment endpoints best suited for use in revealed and stated preference valuation studies.

Energy Production and Consumption

- Energy impacts may be beneficial for small to modest climate change, due primarily to decreases in heating requirements for buildings, but are expected to be dominated by negative impacts in the long-run and at higher levels of temperature change.

- More data and research are needed to evaluate the effects from wildfire and sea level rise on power sector infrastructure, and temperature impacts on electricity production, transmission, and distribution.

Socio-economic and Geopolitical Impacts

- Climate change-induced natural disasters, migration caused by sea level rise and other climate factors, and increasing resource scarcity may promote conflict; however, the policy debate regarding socio-economic and geopolitical impacts from climate change is well ahead of its academic foundation, and sometimes even contrary to the best evidence.

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis

Sponsored by

United States Environmental Protection Agency

U.S. DEPARTMENT OF ENERGY

January 27-28, 2011

Capital Hilton, Washington, DC

Workshop Report:

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis – Part 2

Research on Climate Change Impacts and Associated Economic Damages

March 2011

Workshop Sponsored by:

U.S. Environmental Protection Agency

U.S. Department of Energy

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ICF International

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I. Introduction

This report summarizes the January 27-28, 2011 workshop, *Research on Climate Change Impacts and Associated Economic Damages*, sponsored by the U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE). This was the second in a series of two workshops, titled *Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis.*

This report is organized as follows:

- The first section provides an introduction to the report and the workshop, including context and workshop format.
- The second section provides a summary of the findings and potential improvements to climate change impacts and damages assessment, as identified by workshop participants. This section summarizes and categorizes the wide variety of cross-cutting and sector-specific recommendations highlighted by individual participants over the course of the two-day workshop.
- The third section provides a chronological presentation of the workshop proceedings, including a summary of each presentation and discussion section.
- The appendix to the report provides the final workshop agenda, charge questions, participant list, and extended abstracts of most speaker presentations.

This report serves as the EPA and DOE planning committee's summary of the workshop. It has not received official endorsement from the workshop speakers and other participants.

Context

In 2009 and early 2010, EPA and DOE participated in the interagency working group on the social cost of carbon (SCC). The interagency group used the DICE, FUND, and PAGE integrated assessment models (IAM) to estimate a range of values for the SCC from 2010 to 2050 for use in U.S. government regulatory impact analyses (RIA). The SCC working group reported their findings in February 2010 and the estimated SCC values were first used in the analysis of DOE's Energy Conservation Standard for Small Electric Motors.[1] In preparation for future iterations of this process, EPA and DOE seek to improve the natural science and economic understanding of the potential impacts of climate change on human well-being. This enhanced understanding is also intended to inform ongoing work of the U.S. government to improve regulatory assessment and policy analysis related to climate change.

To help inform this work, EPA's National Center for Environmental Economics and Climate Change Division and DOE's Office of Climate Change Policy and Technology sponsored a pair of invitational workshops in late 2010 and early 2011. The first workshop took place on November 18-19, 2010 and focused on conceptual and methodological issues related to modeling and valuing climate change

[1] See http://go.usa.gov/3fH.

impacts. It also addressed the implications of these estimates for policy analysis. The second workshop, which is the focus of this report, took place on January 27-28, 2011, and reviewed recent research that examines the physical impacts and associated economic damages for a variety of impact categories (e.g., human health, agriculture, sea level rise), with a particular focus on knowledge that might be used to improve IAMs.

Workshop Format

The workshop took place over two days, January 27-28, 2011, at the Capital Hilton Hotel in Washington, DC. The workshop was attended by approximately 100 individuals, including representatives from several U.S. federal government agencies, non-governmental organizations, academia, and the private sector. A full list of workshop participants is available in the Appendix.

The workshop began with opening remarks about recent progress in estimating climate change impacts and valuing climate damages. The vast majority of the workshop consisted of plenary sessions covering research on the following specific impact categories:

- Storms and Other Extreme Weather Events
- Water Resources
- Human Health
- Agriculture
- Sea Level Rise
- Marine Ecosystems and Resources
- Terrestrial Ecosystems and Forestry
- Energy Production and Consumption
- Socio-economic and Geopolitical Impacts

Most sessions included presentations by at least one natural scientist and at least one economist, followed by an open discussion with the audience. The workshop concluded with a panel discussion about incorporating the research on climate change impacts into integrated assessment modeling and brief summary comments by representatives of EPA and DOE.

II. Findings and Potential Improvements Identified by Workshop Participants

Over the course of the two-day workshop, a number of research findings and suggestions for improving the assessment of climate change impacts and damages were identified by the workshop participants. This section aims to summarize and categorize those suggestions.

The participants' suggestions related to impacts and damages assessment both generally and within specific impact categories. As such, the section is organized into two broad categories of comments: cross-cutting comments and sector-specific comments.

The potential improvements and key findings outlined below represent the perspectives of one or more participants but, importantly, do not represent a consensus since none was sought at this workshop.

Cross-Cutting Comments

Throughout the workshop, several participants made comments or suggestions related to impact and damage assessment that apply to more than one impact category. This section is organized into three types of comments:

- Comments related to impact assessment and valuation within sectors
- Comments related to combining impact assessment and valuation from different sectors
- Comments related to research and collaboration priorities

Comments related to impact assessment and valuation within sectors

Throughout the course of the workshop, the participants' comments and suggestions related to impacts assessment and valuation within sectors spanned a wide range of topics, including the following:

- **Clearly incorporate the human response.** Throughout the two-day workshop, numerous participants emphasized the importance of clearly incorporating the human response to climate change when estimating climate change impacts. The human response includes both adaptation and technology development. Many participants emphasized that modeling needs to explicitly account for the human response to climate change impacts, which will greatly affect the magnitude of damages. Participants further emphasized that it is important to clearly articulate what is assumed and included regarding the human response.

- **Build on knowledge of non-climate change impacts and responses.** During the conference, several participants emphasized that climate change impacts (e.g., storms, health impacts) and the corresponding management responses are not without analog. Participants noted that, in many cases, climate change will simply enhance or reduce impacts of other anthropogenic stressors, rather than introduce entirely new stimuli. Participants encouraged the assessment and valuation communities to build on knowledge of existing impacts when modeling future climate change impacts and responses.

- **Use appropriate concepts to measure welfare impacts.** Numerous participants emphasized that GDP is not a measure of welfare, and recommended that alternate measures be used. For example, one participant suggested that consumer surplus is a better measure of welfare. Another participant suggested that direct costs of damage provide a reasonable estimate for global welfare losses.

- **Use appropriate scale and level of detail.** Several participants discussed the importance of scale and level of detail in impacts assessment. Participants suggested that the scale and level of detail required to model each sector is somewhat unique.
    - **Consider both top-down and bottom-up approaches.** Participants noted that both top-down and bottom-up approaches should be considered to estimate climate change

impacts. One participant noted that estimates from the two approaches should converge, confirming the accuracy of the estimates.

- **Better estimate non-linear impacts and damages.** Workshop participants identified several potential improvements related to the assessment of non-linear impacts and damages, including threshold effects, non-linear scaling, and unprecedented changes.

    - **Incorporate threshold effects of physical and biological impacts.** Numerous participants highlighted the thresholds that characterize physical and biological impacts. Participants emphasized the importance of accounting for thresholds, which pervade almost every sector, to robustly estimate impacts. One participant noted that aggregate representations of the natural science can lead to neglect of important threshold effects.

    - **Recognize non-linear character of damages.** Workshop participants emphasized that climate change damages do not necessarily scale linearly with socio-economic variables (e.g., population, income). Several participants highlighted examples of climate damages that relate inversely or non-proportionally with socio-economic variables such as population and income (e.g., sea level rise or health damages). Participants emphasized that it is not appropriate to automatically assume linear scaling of damages.

    - **Use mechanistic approaches.** Several participants recommended the use of mechanistic and process models since statistical extrapolation may not capture non-linear effects of unprecedented levels of change. Participants suggested that impacts modelers rely on basic principles (e.g., plant biophysiology, ocean chemistry) to predict the responses to new climate conditions. However, in cases where climate change impacts are expected to be within or close to the range of past variations, statistical models are appropriate. Participants noted that statistical modeling is more appropriate in some sectors (e.g., agriculture, wildfire impacts) than others.

- **Increase focus on extreme climate events.** Several workshop participants highlighted the need for impacts and valuation assessment to examine the impacts and damages from extreme climate events for incorporation in IAMs and the SCC. Several participants noted that impact studies tend to examine temperature changes of 2.5 to 3 degrees Celsius, neglecting to evaluate the impacts at higher temperature changes. Furthermore, impacts assessment has tended to focus on the means of the probability distribution of impacts, neglecting to evaluate the low-probability, high impact tails of the distribution. Participants emphasized the importance of these high-impact events (e.g., extreme temperature increase, sea level rise) on IAM results.

- **Account for very long-term (beyond 2100) impacts.** Several participants noted the need for impacts and valuation assessment to examine the damages from very long-term (e.g., beyond 2100) impacts. Participants emphasized the importance of these long-term impacts (e.g., ice sheet melting, possible deep ocean anoxia) for IAM results. Participants noted that impact and damage assessments tend to focus on more near-term impacts. They explained that it is critical to model long-term impacts, despite the great uncertainty associated with doing so. Characterization of that uncertainty is important.

- **Distinguish between committed and projected impacts.** Several workshop participants highlighted a need to distinguish between committed and projected impacts in models. Participants emphasized that models need to correctly account for this notion of irreversibility in terms of both positive and negative impacts and damages. They explained that due to the inertia of natural systems, mitigation will not lead to an immediate cessation of some impacts. For example, mitigation can stabilize the rate of sea level rise but cannot prevent the realization of significant, already committed sea level rise.

- **Fully account for non-market and non-use values.** Several participants emphasized the importance of fully incorporating non-market and non-use values to build robust estimates of damages. Several participants recommended that revealed and stated preference estimates and benefit-transfer methods be improved to value these impacts. One participant suggested that problems with both revealed preference and stated preference methods can be mitigated by joint estimation of revealed preference and stated preference data. Another participant recommended collaboration between natural scientists and economists so that impacts assessment endpoints correspond to the items assessed in valuation exercises.

- **More fully incorporate uncertainty**. Throughout the conference, several participants recommended that scientists attempt to characterize the great uncertainty in impacts assessments. IAMs can be used to evaluate the impact of some aspects of sector-specific uncertainty on the SCC.

- **Rigorously evaluate impact models**. Several workshop participants emphasized the importance of rigorously testing, comparing, and evaluating impact models. Several participants noted the important role of Model Intercomparison Projects (MIPs) in improving physical climate models, and suggested that these types of approaches be utilized for a wider range of models. One example of an ongoing impact MIP is the Agricultural Model Intercomparison and Improvement Project (AGMIP).

- **Recognize the potential for unexpected and unpredictable events.** Several participants highlighted the fact that there will likely be unexpected impacts from climate change. For example, one participant described an unexpected outbreak of a shellfish-caused gastrointestinal disease in Alaska due to increases in water temperatures above a previously unknown threshold. Another participant noted that new agricultural pests with unknown characteristics will likely develop as a result of climate change.

Comments related to combining impact assessment and valuation from different sectors

Participants also suggested potential improvements in modeling interactions between different natural and economic systems. These suggestions include the following:

- **Incorporate interactions between sectors.** Throughout both days of the workshop, numerous participants highlighted the importance of including interactions between sectors when estimating impacts. Participants highlighted several examples of interacting sectors, including sea level rise and extreme storms, heat-related health effects and space cooling demand, and water resources and energy demand, among others. Participants noted that interactions and feedbacks may be synergistic or antagonistic, additive, multiplicative, or subtractive. As a result, the cumulative impacts may be larger or smaller than the sum of the individual impacts. Participants further noted the importance of avoiding double-counting when integrating the climate change impacts across sectors.

- **Keep climate change in context.** Over the course of the workshop, several participants emphasized that climate change is only one of many other global, anthropogenic changes impacting the sectors discussed. Participants highlighted the need to incorporate interactions with non-climate stressors and to account for the risk of climate change in relation to other global changes. For example, one participant presented the impacts of water allocation policy on water resources; another participant highlighted needs (e.g., education) other than climate-related health issues competing for investment in developing countries; and, a third participant highlighted coastal management decisions that affect the impacts from relative sea level rise.

Comments related to research and collaboration priorities

Finally, participants made suggestions related to framing a research agenda. These suggestions include the following:

- **Focus research efforts on impacts with greatest magnitude.** Several workshop participants recommended that future research efforts focus on the impacts and damages with potentially the greatest magnitude. One participant noted that it is more important to estimate a high cost damage with some quantified but sizable measure of error, than a lower cost damage with high precision. This recommendation applies both within and among sectors. For example, one participant suggested that it is more important to improve estimates of mortality impacts than to improve estimates of morbidity impacts since the monetized value of mortality impacts tends to overwhelm the monetized value of morbidity impacts. Another participant suggested that IAMs can be used to evaluate the relative magnitude of impacts in different sectors. Research can then be targeted on improving estimates of those impacts with the greatest effect on the SCC.

- **Foster interaction between natural scientists, economists, and modelers.** Throughout the workshop, participants highlighted the importance of increasing collaboration between natural scientists, economists, modelers, and all those involved in impacts assessment, damages valuation, and integrated assessment modeling.

    - **Encourage trans-disciplinary review of IAM damage functions.** Multiple participants recommended that IAM data sources, damage functions, and outputs be reviewed by relevant members of the Impacts, Adaptation, and Vulnerability (IAV) and economic valuation communities. In this way, the communities could ensure that IAMs reflect the current state of the primary literature for each of the impact categories

  - **Link into existing efforts.** One participant recommended that impacts assessment and valuation efforts be coordinated among existing efforts such as the National Climate Assessment, the United Nations Environment Programme (UNEP) Programme of Research on Climate Change Vulnerability, Impacts and Adaptation (PRO-VIA), and other international efforts to improve knowledge on impacts and valuation.

- **Use consistent scenarios.** Workshop participants suggested that consistent climate scenarios should be used in impact and damage assessment. This would facilitate intercomparison of impacts and damages estimates, and would also aid in the integration and combination of these estimates into IAMs.

- **Increase capacity to address challenges.** Numerous participants highlighted a need for additional funding and staff to help address existing impacts and damages assessment challenges. A couple of participants highlighted that IAM development is severely understaffed and underfunded, particularly as compared to general circulation model (GCM) development. One participant highlighted discrepancies in funding between different impact sectors, noting the relative lack of funding for climate change health impacts.

Sector-Specific Comments

The vast majority of the workshop proceedings focused on the current state of research in nine impact categories. This section aims to highlight the key research findings and recommendations for future research for each of the nine impact categories, as identified by workshop participants. The summaries below are based directly on the workshop presentations, and are not intended to be comprehensive.

Storms and Other Extreme Weather Events

- Fewer tropical storms are expected in the future, but the average wind speeds and precipitation totals of the storms that do occur are expected to increase. The intensity of the strongest storms is expected to increase.

- Estimates in the literature for increases in cyclone property damages due to climate change range from 0.002 to 0.006% of Gross World Product (GWP). Increases in property damages from all extreme events (including cyclones) due to climate change, according to one study, range from $47-$102.5 billion (2008 dollars) per year, or 0.008-0.018% of GWP, by 2100.

- Fatalities may increase or decrease due to climate change impacts on extreme events, as deaths from tropical cyclones may decrease more than deaths from other extreme events (e.g., heat waves) increase. Tropical cyclones are expected to continue to be the dominant cause of extreme event-related damages.

Water Resources

- Water demand, supply, and management must be modeled on a river basin scale in order to effectively estimate climate change impacts.

- National estimates from the literature of climate change damages to water resources range from $11.5-$60 billion (2009 dollars) per year for the United States.

- Coupling approaches that model changes using regional hydrologic models and approaches that model changes using regional economic models could help to bridge some gaps in water resources damage estimation.

Human Health

- The most significant health effects from climate change result from diarrhea, malnutrition, and malaria.

- The World Health Organization (WHO) estimates that the costs to treat climate change-related cases of diarrhea, malnutrition, and malaria in 2030 would be $4 to $13 billion. This would be a 3% increase in diarrhea cases, a 10% increase in malnutrition cases, and a 5% increase in malaria cases.

- Health impact valuation depends largely on mortality valuation, particularly in developing countries, and particularly among children. Appropriately adjusting the value of a statistical life for income is critical for accurate valuation.

- Health impacts in developing countries must be considered in the context of other stressors.

Agriculture

- Estimates in the literature project the global range of yield changes in the 2050s to be approximately -30 to +20%, compared with 1990, under an A2 SRES emission scenario, which corresponds to a 2.3°C mean global temperature increase from base temperatures (1961-1990).

- Global effects of climate change on agriculture are expected to be positive on average in the short term and negative in the long term. The location of the inflection points, with respect to climate change severity over time, where impacts change from positive to negative are unknown.

    - CO_2 fertilization from increasing carbon dioxide concentrations will benefit some plants (C_3 plants) more than others (C_4 plants). Elevated CO_2 concentrations especially benefit weeds, which are particularly good at taking advantage of high CO_2 concentrations.

- Agriculture's contribution to only 2-3% of U.S. GDP is due, in part, to the paradox of value and price, where rare, nonessential goods cost more than essential goods. However, the highly inelastic nature of agricultural demand means that even a small reduction in agricultural production from climate change could result in large price changes and large welfare losses.

- Adaptation and technology change can help to mitigate the impacts of climate change on agriculture. A key challenge will be producing heat and drought tolerant plants with high yields.

Sea Level Rise

- Climate-induced sea level rise will be compounded by subsidence in many densely-populated coastal areas.

- The greenhouse gases emitted so far have committed the planet to a significant amount of sea level rise that will be fully realized over coming centuries. Emissions abatement may stabilize the *rate* of sea level rise, but not reduce the globe's current commitment to sea level rise.

- The valuation of sea level rise damages depends heavily on wetland values and on adaptation.

Marine Ecosystems and Resources

- Increasing atmospheric CO_2 concentrations cause ocean CO_2 concentrations to increase, decreasing ocean pH, and decreasing saturation states for calcite and aragonite, which are used by marine animals to produce calcareous parts (e.g., shells).

- Damages from decreased mollusk harvest revenues due to a 0.1-0.2 ocean pH decrease are estimated at $1.7 to $10 billion in net present (2007) value losses through 2060.

- Assessments using the following three approaches would be beneficial to estimate marine impacts: a bio-climate envelope, which evaluates species tolerance to changing environmental variables, to provide key first pass estimate; minimum realistic models, which represent only the most important components of a specific system, on high value fisheries; and ecosystem and food web models to assess component interactions.

- A wide variety of studies to estimate damages is needed, using both revealed and stated preferences, to estimate total economic value of marine ecosystems and resources. Analyzing the results available from multiple existing studies could be used in a benefit transfer study to estimate economic value by transferring available information into the appropriate context.

Terrestrial Ecosystems and Forestry

- Three major types of terrestrial ecosystem impacts are expected: changes in vegetation distribution and dynamics, wildfire dynamics, and species extinction risks. Predicted global extinctions range from relatively low levels up to 60% of species.

- Understanding changes in pest outbreaks, interior wetlands, and snow pack are important gaps in impacts assessment.

- Natural scientists and economists need to work together to identify biophysical impacts assessment endpoints that correspond to the items assessed in valuation exercises.

Energy Production and Consumption

- Energy impacts may be beneficial for small to modest climate change, but are expected to be dominated by negative impacts in the long-run.
- In the U.S. and across the group of industrialized countries, energy use and expenditures for space conditioning is expected to decrease due to near-term warming, since decreases in energy demand for heating are likely to be greater than increases in energy demand for cooling. Net demand changes may be quite different from this conclusion over the long-term and for other regions.
- More data and research are needed to evaluate wildfire and sea level rise impacts on power sector infrastructure, and temperature impacts on electricity production, transmission, and distribution.

Socio-economic and Geopolitical Impacts

- Climate change-induced natural disasters, migration caused by sea level rise and other climate factors, and increasing resource scarcity may promote conflict.
- Estimates for the number of future environmental refugees range from 50 million by 2010 to 1 billion by 2050. These estimates include numerous environmental causes for displacement, including climate change.
- The policy debate regarding socio-economic and geopolitical impacts from climate change is running well ahead of its academic foundation, and sometimes even contrary to the best evidence.

III. Chronological Presentation of Workshop Proceedings

This section presents the proceedings of the workshop in chronological order, including the following components: workshop introduction; session presentations and discussion sessions; panel discussion; and closing remarks. The following summary represents statements from one or more workshop participants but, importantly, represents neither the views of EPA or DOE, nor a consensus, since none was sought at this workshop.

Workshop Introduction

The workshop introduction included a welcome from Dr. Elizabeth Kopits of EPA, followed by opening remarks from Dr. Michael Oppenheimer of Princeton University and Dr. William Cline of the Peterson Institute for International Economics, as well as questions about the opening remarks.

Welcome

The workshop commenced with a welcome by Dr. Elizabeth Kopits. She noted that this workshop was the second of two EPA- and DOE-sponsored workshops in preparation for future efforts to estimate the social cost of carbon. She mentioned the previous meeting focused on integrated assessment models, the 2009-2010 SCC process, and broad conceptual issues associated with integrated assessment. She explained that the second workshop would focus on a more detailed review of the quantitative research on climate change impacts and associated damages, which underpins integrated assessment models. She noted that in some sectors, the science and economics may have evolved enough to indicate ways in which IAM damage functions can be improved; while in other sectors, it may only be possible to enumerate research gaps and priorities. She highlighted the desire to facilitate increased dialogue and coordination between natural scientists and economists, noting that each session of the workshop would pair a natural scientist with an economist and would include interdisciplinary dialogue.

Opening Remarks

Progress in estimating climate change impacts

Following Dr. Kopits' introduction, Dr. Michael Oppenheimer of Princeton University presented opening remarks on past and potential future progress in estimating climate change impacts. He noted that the systematic assessment and valuation of potential climate change impacts and damages dates back to the 1970s. He explained that there have been recent advances in process-based and statistical modeling of physical exposure and impacts. These advances include improvements in general circulation model resolution and downscaling; statistical modeling of agriculture, migration, and conflict responses; and deployment of GIS data.

In contrast, there has been slow and limited progress in accounting for adaptation capacity and human responses. Dr. Oppenheimer noted that current approaches to incorporate adaptation responses are obscure, that there is little understanding of the gap between adaptation capacity and implementation, and that indirect effects of human responses (e.g., of migration) have not been assessed. He emphasized the importance of incorporating the human response in climate change impacts modeling.

Dr. Oppenheimer then presented five emerging areas in estimating climate change impacts. First, he presented the indirect and remote consequences of human responses, such as human population migration or shifts in human activities (e.g., agriculture) that affect resources and populations at a distance. Second, he presented the interacting effects of adaptation and mitigation, highlighting the biodiversity, food price, and political ramifications of biofuel development and the political reverberations of geo-engineering. Third, he presented the complexity of interacting systems and stressors. For example, he noted how upstream water diversion can cause deltaic subsidence which interacts with sea level rise. Fourth, he presented complexities associated with climate extremes and disasters, such as the local specificity of exposure and vulnerability, and the learning that may occur as rare events become more frequent. Fifth, he presented the dynamic nature of vulnerability, which evolves with development and changes as learning competes with mal-adaptive and risk-shifting behavior. He noted the complexities associated with diverse potential development pathways and the existing gap between top-down and bottom-up estimates of impacts.

Progress in valuing climate damages

Next, Dr. William Cline of the Peterson Institute for International Economics presented opening remarks on past and future progress in valuing climate damages. He discussed the different historical approaches to estimating the SCC and emphasized the importance of catastrophic risk valuation and discount rate selection. Dr. Cline emphasized the role of the pure rate of time preference in Ramsey discounting, noting the use of a zero pure rate of time preference in several estimates. Dr. Cline also emphasized the effect of uncertainty, noting that insuring against catastrophe would warrant aggressive action even without a zero pure rate of time preference.

Regarding catastrophic risks, Dr. Cline noted that some have been considered in damage valuation, including collapse of the ocean conveyor belt, collapse of the West Antarctic Ice Sheet, and a runaway greenhouse effect from methane release. Dr. Cline then presented the possibility of hydrogen sulfide release from deep ocean anoxia due to anaerobic bacteria buildup caused by sea level rise and shutdown of the ocean conveyor belt. He explained that the resulting elevated hydrogen sulfide levels could be toxic to plants and animals and could cause mass extinction. He noted that this risk should not be ignored, despite the fact that it would likely not occur for 2000 years or more. In order to account for very long term but catastrophic damages, Dr. Cline argued that contingent valuation might be necessary, as the use of even the lowest interagency discount rate produces numbers too low to justify action to prevent a risk so far in the future. He suggested that super-contingent valuation may be helpful to value such catastrophic risks. He noted that the contingent valuation implied by the Copenhagen pledge to reduce emissions from developing countries far exceeds current IAM estimates for the social cost of carbon.

Regarding the discount rate, Dr. Cline noted that a descriptive approach using Treasury Inflation Protected Securities yields a discount rate lower than what was used by the interagency process. Dr. Cline then noted the importance of the elasticity of marginal utility when using a prescriptive approach, suggesting that a value of 1.5 is more appropriate than a value of 1 as proposed by Stern or a value of 2 as proposed by Weitzman.

Dr. Cline noted that, if targets are set, the SCC is defined as the marginal abatement cost along the least cost pathway to achieving the targets. Finally, Dr. Cline suggested that the interagency group should consider an insurance approach to determining the SCC.

Questions

In response to a question from the audience, Dr. Oppenheimer noted his interest in statistical approaches. He emphasized that estimates from top-down approaches and bottom-up approaches should converge, thereby giving one indication of their reliability.

During the question and answer session, one participant suggested that the time scale of long-term CO_2 effects is tens of thousands years, two orders of magnitude larger than what is typically considered. Dr. Cline noted that he may have contributed to the use of a scale of hundreds of years, but that typical discount rates imply that what happens after 80 years is of little consequence. A second participant agreed with Dr. Cline in preferring a precautionary or insurance approach over a cost-benefit approach. The participant noted that as the marginal benefit of the abatement curve approaches vertical, the precautionary benefits of abatement increases dramatically.

A third participant suggested that adaptation will occur on a global scale and asked how adaptation could be incorporated into the SCC and U.S. policies. In response, Dr. Oppenheimer first noted the many levels of human response, from individual to international. He then suggested that many studies do not consider the human response at all. Finally, he noted that a comprehensive solution to incorporate adaptation may not yet be available, but that it is important to strive to do better and to incorporate the human response to impacts at whatever level is possible.

Storms and Other Extreme Weather Events

Following the workshop introduction, there were nine sessions, each covering a specific impact category. The first session covered the impacts and damages from storms and other extreme weather events. The session was moderated by Dr. Alex Marten of the U.S. Environmental Protection Agency and included presentations by Dr. Tom Knutson, National Oceanic and Atmospheric Administration (NOAA); and Dr. Robert Mendelsohn, Yale University.

Impact of Climate Change on Storms and Other Extreme Weather Events

Dr. Tom Knutson, of NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), presented the effects of climate change on tropical cyclones. Most of his presentation focused on the findings from a World Meteorological Organization (WMO) study. The study sought to determine two things: whether the human impact on hurricanes is detectable and what future climate change implies for hurricane activity.

Regarding the detection and attribution of climate change in tropical cyclone activity, the study concluded that it remains uncertain whether past changes in tropical cyclone activity exceed natural variability levels. For example, while the frequency of past tropical cyclone activity is correlated with increases in sea surface temperature, the trends disappear when storm counts are adjusted to account for improved storm observation data.

To evaluate the future implications of climate change for tropical cyclone activity, the study considered the changes associated with the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES)[2] A1B scenario. To predict future activity, the study used high resolution atmospheric models, regional dynamical downscaling models, and statistical/dynamical techniques that are able to reproduce historic interannual variability. The WMO expert team made five general conclusions regarding the effect of future climate change on tropical storm activity.

First, the models almost unanimously predict that there will likely be fewer tropical storms globally, with predictions ranging from no change in frequency to a decrease of 34%. There is greater uncertainty regarding the frequency of storms in individual basins (e.g., the Atlantic), though storms in the southern hemisphere decrease in frequency fairly consistently in the different models.

Second, the experts predict a likely increase in average hurricane wind speeds (intensity) globally, with increases ranging from two to 11 percent. Dr. Knutson noted that this statistic does not necessarily apply to individual basins.

Third, the experts predict that there is a greater than 50% chance that the frequency of very intense hurricanes will increase by a substantial fraction in some basins. Fourth, climate change will likely result

[2] http://www.ipcc.ch/ipccreports/sres/emission/index.htm

in higher rainfall rates in hurricanes. The models predict a roughly 20% increase within 100 km of a storm. Fifth, sea level rise is expected to exacerbate storm surge impacts, even if storms themselves do not change**.**

Dr. Knutson summarized these conclusions by explaining that the experts predict fewer tropical storms overall, but an expanded range of storm intensity. The combination of these two changes will result in an increased number of intense storms. Throughout his presentation, Dr. Knutson emphasized the wide range of estimates and disagreement among different models for various tropical cyclone metrics.

Dr. Knutson finished his presentation by noting several factors that might exacerbate the study's projections. These factors include changes in the vertical profile of warming, the El Nino / La Nina pattern of warming, wind shear, and ocean heat transport.

Global Damages from Storms and Other Extreme Weather Events

Dr. Robert Mendelsohn of Yale University expanded on Dr. Knutson's presentation by discussing the effects of climate change on all extreme events, and by delving into the damages associated with these effects. Dr. Mendelsohn examined cold events, drought, floods, hail, heat waves, tornadoes, thunderstorms, tropical cyclones, and extratropical severe storms. His presentation aimed to describe how climate change affects future extreme events, to reflect any underlying changes in future vulnerability, to estimate damage functions for each type of extreme event, and to describe damages from future extreme events caused by climate change.

First, Dr. Mendelsohn considered the change in damages and deaths due to changes in future income and population, without considering climate change effects. He showed that damages increase greatly due to these socio-economic changes, noting that damages from heat waves increase most dramatically and damages from tropical cyclones are the greatest in magnitude. Next, he showed that deaths do not follow the same pattern, with deaths associated with some extreme events (e.g., heat waves) predicted to increase, while others (e.g., those associated with floods, tropical cyclones) predicted to decrease. He noted that deaths increase with increased population, but decrease with increased income.

Dr. Mendelsohn next summarized estimates of changes in cyclone damages due to climate change. He noted that increases in damages have been estimated at 0.002%-0.006% of Global World Product. He noted that the tropical cyclone generator, which models cyclone development, estimates different results in different basins, but shows a consistent increase in tropical cyclone power in the Atlantic and Northwest Pacific basins.

Dr. Mendelsohn then regressed damages and deaths on different variables to develop damage functions. He noted that, using U.S. data, damages increase with both income and population density, but less than proportionally. Using international data, however damages increase less than proportionally with income, but decrease as population density increases. Dr. Mendelsohn noted that the impacts of climate change due to cyclones will be greatest in North America and Asia. He further noted that the impacts from other extreme events are likely to be less significant by an order of magnitude than those from tropical cyclones.

Dr. Mendelsohn explained several limitations associated with this estimation process, including: uncertainty of non-hurricane impacts; the coarseness (e.g., country-scale) of some of the key data; the need for better data about damages, extreme events, and the relationship between them; the paucity of information on ecosystem impacts; and the lack of explicit incorporation of adaptation in impact models.

Dr. Mendelsohn concluded with a brief summary of results. He noted that predicted climate change impacts from all extreme events (including tropical cyclones) range from $47 to $100 billion per year by 2100. This is equivalent to 0.008-0.018% of GWP by 2100. Finally, he noted that climate change has a mixed effect on fatalities because tropical cyclone deaths may fall more than other deaths increase.

Discussion: Storms and Other Extreme Weather Events

During the question and answer session, a couple of participants asked about intersectoral impacts, particularly the interaction between storms and sea level rise. Dr. Mendelsohn noted that the effects of sea level rise and storms are at least additive, but may be interactive and more than additive.

A couple of participants questioned the result that the additive effects of climate change on tropical storms will result in a decrease in deaths. Dr. Mendelsohn explained that this result is due to the predicted decrease in tropical cyclone intensity in the Indian Ocean due to climate change, where approximately 90% of current tropical cyclone deaths occur. He noted that deaths are predicted to increase in every part of the world except for Southern Asia, but that the magnitude of the increases will be small. He also clarified that his work did not monetize deaths.

Several participants asked about the estimation of deaths from heat waves. Dr. Mendelsohn explained that with heat waves, it is the variance rather than the average temperature that matters, since humans are able to adapt to higher average temperatures. He noted that his work does not include ecosystem effects, such as mammalian die-off due to heat waves, nor does it include empirical work on human labor changes due to temperature increases. One participant challenged the assertion that only variance matters, noting that humans are not able to live at very high temperatures. Dr. Mendelsohn clarified that only variance matters within the context of extreme events.

One participant asked whether a valuation of impacts on agriculture and famine was incorporated. Dr. Mendelsohn noted that agriculture effects are incorporated but famine effects are not. Another participant asked whether the predicted relative contribution to damages from different extreme events will change significantly as more research is conducted. Dr. Mendelsohn noted that damages from floods and perhaps heat waves may prove to be more important than currently predicted. However, he explained that it was unlikely that they would increase by an order of magnitude, thus concluding that tropical cyclones will continue to have the greatest impact.

Water Resources

The second session covered the impacts and damages to water resources. The session was moderated by Dr. Robert Kopp of DOE and included presentations by Dr. Ken Strzepek, University of Colorado at Boulder and Massachusetts Institute of Technology; and Dr. Brian Hurd, New Mexico State University.

Hydrological/Water Resource Impacts of Climate Change

Dr. Kenneth Strzepek of the University of Colorado at Boulder and the Joint Program on the Science and Policy of Global Change at the Massachusetts Institute of Technology commenced the second impact-specific discussion by discussing how impacts to water resources can be incorporated into IAMs. Dr. Strzepek explained that water resources encompass a broad spectrum of issues and appear in 18 of the 30 chapters of the IPCC Working Group 2 report.

He explained that, globally, the largest water use is agriculture, while, in the United States, the largest use is thermal cooling for energy production. Dr. Strzepek emphasized the importance of using the appropriate spatial and temporal scale when modeling impacts to water resources. He noted that disaggregation is necessary in order to properly model water supply and demand. Dr. Strzepek explained that a regional or national scale, as often used in IAMs, is far too course to properly model water resources and crops, since the local location of water is critically important and aggregation averages water excesses and water shortages. Using several examples, he illustrated how aggregation can misrepresent the supply and demand of water resources. Instead, Dr. Strzepek suggested that a river basin scale may be more appropriate.

Dr. Strzepek further suggested that water management systems must be modeled at the basin-level to appropriately describe impacts and, especially, adaptation. He noted that water management systems can adapt to changing water supply by increasing water storage capacity to level supply. He noted that modeling water management is crucial since cross-sectoral impacts are greater than sectoral impacts, since different uses are forced to compete for available water. Dr. Strzepek also explained that the metrics used to model water resources are important. For example, different metrics of drought produce very different results.

Next, Dr. Strzepek explained that flooding and storms are very important when considering climate change impacts to water resources. He noted that a lot of work has been conducted on the effects of drought, but that flooding is particularly harmful as it can cause serious damage to capital investments, including infrastructure such as roadway bridges.

Finally, Dr. Strzepek emphasized that threats to water resources must be considered in the context of other global changes. He illustrated that municipal and industrial water demand and environmental policy threaten agricultural water supply more than climate change. He underscored that the effects of climate change must be considered in relation to other uncertainties and stressors. He also mentioned that addressing uncertainty is important.

In response to a question, Dr. Strzepek explained that water management and technological improvements can ameliorate some impacts (e.g., by leveling supply using dams), however a lack of water due to climate change could still have serious implications.

Estimating the Economic Impact of Changes in Water Availability

Following Dr. Strzepek's presentation, Dr. Brian Hurd of New Mexico State University presented estimates of the economic impacts of climate-related changes in water availability. Dr. Hurd again emphasized the complexity of water and water systems, noting the spatial and temporal variability as well as the variability in uses, infrastructure, and vulnerability. He noted that statistical modeling is nearly impossible and that process models work better for estimating the magnitude of changes outside of historical experience. He highlighted the importance of behavioral aspects such as adaptation and optimization.

Dr. Hurd then presented national-level estimates from the literature of annual economic impacts of climate change on water resources. Estimates in the literature range from $7 billion to $60 billion (2009 dollars), under varying assumptions. These estimates arise both from studies that use a hydro-economic model to aggregate benefits and costs and from studies that use regional economic models to estimate impacts on jobs, income, and GDP. He noted that despite very different methodologies, the estimates are consistent in order of magnitude and share of GDP. He noted the counter-intuitive result from some studies that GDP may increase where impacts are greatest, since disasters can increase the number of jobs in certain sectors and locations.

Dr. Hurd concluded with a list of knowledge gaps that limit current estimates and provide areas for future improvement. These gaps include: understanding changes in extreme events; the role of water rights, and federal and state regulation; administrative constraints in adaptation; projections of market prices and trade flows of agricultural and other water-intensive products; measuring, monitoring, and modeling groundwater; water security and food security issues; and assessing and measuring economic outcomes of water quality. He suggested that coupling approaches that model changes using regional hydrologic models (hydro-economic) and approaches that model changes using regional economic models (dynamic system simulation) approaches could help to bridge some gaps.

Discussion: Water Resources

During the question and answer session, one participant questioned the negative impacts for New York State presented by Dr. Hurd, given her understanding that climate projections indicate that water will increase in New York. Dr. Hurd clarified that the study in question only presented impacts from projected drought scenarios without looking at projected increases in water availability. Dr. Strzepek further noted that models indicate an increase in winter precipitation for New York. Without reservoir capacity, New York would be unable to harness the additional water.

A second participant highlighted an example of non-climate global changes interacting with climate change impacts. He noted that there is a movement by EPA to make closed-cycle cooling the standard for thermoelectric power, which would eliminate the 48% of U.S. water currently used for power plants. A third participant questioned whether water withdrawals or water consumption is more important from a modeling and policy perspective. He noted that cooling towers reduce withdrawals but increase consumption. Dr. Strzepek explained that this is a very complicated issue that is affected by temperature and runoff in addition to consumption. He noted that within the United States the issue is most relevant in the western United States.

A fourth participant asked for global estimates of damages to tie this sector into SCC estimates. Dr. Hurd noted that he had focused the research for his presentation on U.S. impacts. Dr. Strzepek cited a series of studies by the World Bank that estimate adaptation costs for water resources at $80-100 billion per year for developing countries. He noted that additional global work has been funded and is underway.

A fifth participant asked about the importance of variability with regard to water resources. Dr. Strzepek emphasized that variability, as well as seasonality, is crucial. However, he noted that the GCMs have trouble capturing this variability. Dr. Hurd further noted that the literature is not well developed on the real impact and economic estimates of those changes. Another participant asked about the attitude of water managers towards variability. Dr. Strzepek explained that water managers tend not to worry about variability because engineers overbuild infrastructure to withstand 100-year events. Since some water managers believe that the uncertainty about what constitutes the current 100-year event dwarfs the potential effects of climate change, they also believe that if systems are prepared for current variability, they are also prepared for climate change.

Human Health

The third session covered the impacts and damages to human health. The session was moderated by Dr. Charles Griffiths of EPA and included presentations by Dr. Kristie Ebi, Carnegie Institution for Science; and Dr. Maureen Cropper, Resources for the Future and University of Maryland at College Park.

Climate-Associated Changes in Health Conditions/Diseases and Air Pollution

Dr. Kristie Ebi of the Carnegie Institution for Science introduced the third impact category with her presentation on climate-associated changes in health outcomes. Dr. Ebi presented several different health conditions that will be affected by climate change, highlighting malnutrition, diarrheal disease, and malaria. Since climate change is never the direct cause of death, she noted that deaths due to climate change have to be modeled.

Dr. Ebi began by presenting an overview of the direction and magnitude of different climate change health impacts, as presented by the IPCC Fourth Assessment Report (AR4). The only net positive impact predicted by the report is a reduction in cold-related deaths. Meanwhile, the report predicts net negative impacts from increases in malaria; malnutrition; deaths, disease, and injuries from extreme weather events; cardio-respiratory disease from changing air quality; infectious disease; and diarrheal disease.

Dr. Ebi noted that the current impacts of these diseases are enormous. For example, under-nutrition results in 35% of child deaths, 11% of the total global burden of disease, and 21% of disability-adjusted life-years (DALYs) for children younger than 5 years. When all the effects of malnutrition are considered (including loss of cognitive function, poor school performance, and loss of future earning potential), the total estimated costs of environmental risk factors could be as high as 8-9% of a typical developing country's GDP in South Asia or Sub-Saharan Africa. Dr. Ebi noted that the scale of current impacts means that even small increases in the impacts will have significant effects. For example, even small increases in temperature could result in enormous increases in the number of mosquito vectors and thus in the prevalence of malaria.

Dr. Ebi then discussed the major regional differences in impacts and their concomitant equity implications. While diarrheal disease has impacts across the globe, the major burden exists in India and

Africa. The burden of malaria lies almost exclusively in Africa. These distributional differences extend to the country level, with different areas within a country experiencing very different rates of disease.

Dr. Ebi noted that current models do not account for complexities and interactions between different impacts. For example, poor nutritional status promotes infectious disease and vice versa. She also mentioned that higher temperatures can lead to increased ozone formation, which affects anyone with compromised lung function or cardiovascular disease.

Dr. Ebi next presented estimates of the costs to treat climate change-related illness from the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC estimates that the costs to treat climate change-related cases of diarrhea, malnutrition, and malaria in 2030 would be $3,992 to $12,603 million. This accounts for a 3% increase in diarrhea cases, a 10% increase in malnutrition cases, and a 5% increase in malaria cases. Dr. Ebi then noted that there will likely be unexpected climate change health impacts. As an example, she described the unexpected outbreak of a shellfish-caused gastrointestinal disease in Alaska, which was caused by increases in water temperatures above a previously unknown threshold.

Dr. Ebi finished her presentation with an extensive list of research needs emphasizing the significant need for work to understand exposure-response, to model impacts, to take into account other drivers, and to understand adaptation. In response to a question, Dr. Ebi noted the need for research on threshold effects. She noted that the health sector has been severely underfunded with regards to other climate change effects, particularly in the United States.

Estimating the Economic Value of Health Impacts of Climate Change

Dr. Maureen Cropper of the University of Maryland and Resources for the Future built on Dr. Ebi's presentation with a presentation on estimating the economic value of the health impacts of climate change. Dr. Cropper noted that economists should value damages after adaptation, plus the costs of adaptation. However, she focused her presentation on valuing the health impacts themselves.

Dr. Cropper noted that health impact valuation depends largely on mortality valuation, particularly in developing countries, and particularly among children. She emphasized that, by far, the largest damages are due to mortality. She underscored that it is better to estimate a crucial issue with some measure of error (e.g., mortality), than a less important issue with high precision (e.g., morbidity).

Dr. Cropper next discussed two different approaches to valuing increased risks of mortality and morbidity. First, the human capital-cost of illness (COI) approach values increases in mortality risk using the present discounted value of forgone earnings, and values an injury by the associated medical costs and lost productivity. Second, the value of a statistical life (VSL)-willingness to pay (WTP) approach values increases in mortality risk using what people will pay for small reductions in risk of death, and values an injury by adding the willingness to pay to avoid pain and discomfort to the COI value. Dr. Cropper noted that the VSL can be estimated using revealed preference studies (e.g., based on compensating wage differentials, purchase of safety equipment) or stated preference studies.

Dr. Cropper noted that there have been dozens of VSL studies in high-income, and even middle-income countries, but that there has only been one study in a low-income country (Bangladesh). She explained that the VSL can be transferred from one country to another using the income ratio between the two countries and the appropriate income elasticity. Dr. Cropper noted that the income elasticity is usually assumed to be one, however, many other factors that affect the VSL differ between countries, including risk preferences, life expectancy, and consumption. Dr. Cropper showed evidence from the literature that the income elasticity should be greater than one and should increase as income falls. Based on a couple of studies, she suggested that an income elasticity of 1.5 is more appropriate.

Dr. Cropper then discussed the difficulties associated with estimating the VSL for children. She explained that an accepted method is the use of parents' willingness to pay to reduce risks to their children. In high income countries, this method suggested that the VSL for a child is approximately twice that of an adult. However, parents' WTP may be different in countries where one out of five children dies before age five. She suggested that, in the interim, the same VSL be used for adults and children until a sensitivity analysis can be conducted.

Finally, Dr. Cropper discussed valuing morbidity. She noted that most estimates capture the value of lost productivity and the cost of medical treatment but that most estimates neglect the value of discomfort, inconvenience, and pain. She again noted that morbidity damages are significantly smaller than mortality damages, once more suggesting that it is most important to refine mortality estimates. She finished by noting that there may be other relevant health impacts, such as the macroeconomic impacts of malaria or the impacts of malnutrition on human capital formation, which could each affect economic growth.

Discussion: Human Health

During the discussion session, a couple of participants challenged the use of WTP as the most appropriate way to frame and value climate impacts. Instead, the participants suggested that willingness to accept compensation be used. This suggestion is based on the fact that the people that cause climate change (e.g., developed countries, older generations) tend not to be the people that are impacted by climate change (e.g., developing countries, younger generations). Dr. Cropper defended the use of WTP, emphasizing that WTP reflects market preferences.

During the discussion, Dr. Ebi and Dr. Cropper emphasized that climate change is just one of many stressors on developing countries. Dr. Cropper suggested that it is important to keep climate change in context and acknowledge that developing countries may prefer to invest in, e.g., education rather than climate change mitigation or adaptation. She suggested that viewing climate change impacts independently would result in over-allocation of resources to climate change issues. One participant asked whether countries should invest in mitigation or in current health impacts. Dr. Ebi suggested that the money for the two different issues does not tend to come from the same sources. In response to another question, she emphasized that the smallest portfolio of funding is directed towards climate change health issues, since it is difficult to attribute health impacts to climate change.

One participant asked how demographic transitions affect health impacts of climate change. Dr. Ebi explained that the issue is complex. She noted that many countries are already undergoing a demographic transition. However, she further noted that there are limits on how much wealth can address health impacts. As an example, Dr. Ebi explained that malaria and dengue control is extremely difficult and requires discovering the right balance of components and maintaining efforts.

A participant asked about impacts on labor productivity. Another participant explained that he used a biophysical model of the human body to estimate how much labor a person can produce at different temperatures and humidity levels. He explained that normal non-air conditioned labor is not possible above certain thresholds. He concluded that without adaptation, labor productivity could fall by 30 percent and GDP could fall by 10 to 15 percent. A final participant asked what reference case should be used when evaluating the SCC and asked if and how current adaptation efforts will affect the reference case. Dr. Ebi agreed that current adaption would change the reference case.

Agriculture

The fourth session covered the impacts and damages to agriculture. The session was moderated by Dr. Charles Griffiths of EPA and included presentations by Dr. Cynthia Rosenzweig, National Aeronautics and Space Administration (NASA) Goddard Institute of Space Studies; and Dr. Wolfram Schlenker, Columbia University.

Biophysical Responses of Agro-ecosystems to Climate Change

Dr. Cynthia Rosenzweig of the NASA/Goddard Institute for Space Studies introduced the fourth impact category by presenting the biophysical climate change effects on agro-ecosystems. Dr. Rosenzweig began by presenting observed climate change impacts on agriculture, which include high temperature effects on rice yield, earlier planting of spring crops, increased forest fires, change in pests, and declines in livestock productivity.

Dr. Rosenzweig explained that studies show insects are emerging earlier, including agriculturally beneficial insects such as bees, as well as pests such as the potato beetle. She noted that climate change may cause new pests to emerge, one of the potential climate change surprises. Next, Dr. Rosenzweig showed that increasing carbon dioxide concentrations benefit C_3 plants (e.g., wheat, rice, soybean, barley) more than C_4 plants (e.g., corn, sorghum, sugarcane), as C_4 plants are already able to concentrate CO_2. She emphasized that increasing CO_2 concentrations benefit weeds in addition to crops, noting that weeds are favored as they are particularly good at taking advantage of high CO_2 concentrations.

Next, Dr. Rosenzweig explained that increasing temperatures can speed up growth cycles. This acceleration negatively impacts yields, as crops have less time to accumulate carbohydrates. She further noted that high temperature stress during critical growth periods (e.g., pollination) could have detrimental effects. Dr. Rosenzweig then described the effects of changes in precipitation. She noted that both drought stress and excess water can be damaging to yields.

Dr. Rosenzweig presented temperature maps that show warming is expected to be greatest over land and at the highest northern latitudes. Similarly, she showed maps that indicate increases in precipitation are very likely in the high latitudes, while decreases are likely in most subtropical land regions. She showed that the most negative yield effects are expected in the lower latitudes, where developing countries are, while the less negative or more positive effects will be in the higher latitudes.

Dr. Rosenzweig noted that globally, the literature consistently estimates the range of yield changes to be approximately -30 to +20 percent. The estimates of the most negative effects range from -32 to -35 percent, while the estimates of the most positive effects range from 19 to 25 percent. Dr. Rosenzweig then showed that global effects of climate change are expected to be positive in the short term and negative in the long term. She noted that the location of the inflection points where impacts change from positive to negative are unknown.

Dr. Rosenzweig then presented the three main approaches to model agricultural impacts, along with advantages and disadvantages, data requirements, spatial resolution, and level of uncertainty for each approach. First, statistical approaches use historical data to estimate statistical relationships between crop and climate variables. These relationships are then used to project climate impacts on yield. Second, expert system approaches use statistical relationships between observed crop yields and observed climate variables to estimate production potential. Third, dynamic process crop models use data and modeled relationships to explicitly simulate the various processes affected by climate. She noted that the graphs that show increasing yield responses to low levels of warming were assembled using largely incomparable data points from very different models and studies, using different coefficients.

Following her presentation of modeling approaches, Dr. Rosenzweig discussed the ability of adaptation and technology to modulate the biophysical impacts. She presented three levels of adaptation, each with increasing benefit, as well as increasing complexity, cost, and risk. The first level includes adjusting varieties, planting times, and spacing. The second level includes actions such as diversification and risk management. The third level includes transformation from land-use or distribution change. She demonstrated that adaptation is not always possible or complete.

Finally, Dr. Rosenzweig finished with a list of gaps and uncertainties related to the biophysical climate change impacts on agriculture. She emphasized the importance of precipitation impacts, which are critical but relatively unknown. Other gaps and uncertainties include: simulating extreme weather events; interactions between warmer temperatures, CO_2, and ozone; interactions between evapotranspiration, soil moisture, crop yield, and water availability; pests; scale effects; yield gaps and plateaus; and multi-model comparisons and assessments. She emphasized the importance of rigorously testing and comparing models, and noted AGMIP, the Agricultural Model Intercomparison and Improvement Project, which is a relatively new effort to assess and ultimately improve agricultural models.

Estimating the Economic Impact of Climate Change in the Agricultural Sector

Next, Dr. Wolfram Schlenker of Columbia University and the National Bureau of Economic Research gave his presentation on estimating the economic impact of climate change in the agricultural sector. First, Dr. Schlenker presented the fact that U.S. agriculture only accounts for two to three percent of U.S. GDP, which might be interpreted to mean that agricultural impacts are negligible. He explained that the low contribution to GDP results from the paradox of value and price, where rare, nonessential goods cost more than essential goods. Through a series of graphs he showed that GDP is not a welfare measure and suggested that consumer surplus is a better option. He showed that because agricultural demand is highly inelastic, a small reduction in agricultural production (e.g., from climate change) results in large price changes and could lead to large welfare losses (i.e., reductions in consumer surplus).

Then, Dr. Schlenker discussed the global importance of U.S. agriculture. He explained that corn, rice, soybeans, and wheat contribute 75 percent of the calories consumed by humans worldwide. World caloric production has been trending upward, resulting in falling real prices over the 20th century. Dr. Schlenker explained that the U.S. share of caloric production has been roughly constant at around 23 percent for the last 50 years. He noted that this share is larger than Saudi Arabia's share of oil production, which means that impacts on U.S. yields have the potential to influence world markets.

Next, Dr. Schlenker presented a statistical analysis examining the link between temperature and yields. He explained the highly non-linear relationship between yields and the number of exposures to particularly cold or warm days (above 84-86°F). He noted that the negative slope of impacts at high temperatures is ten times greater than the slope at low temperatures, which implies large yield declines if maximum temperatures increase significantly. He concluded that the driving force behind climate change impacts on agriculture is extreme heat, with impacts depending on both the baseline temperature and the predicted increase.

Dr. Schlenker then explored the ability of technological progress to mitigate climate impacts. Through a series of graphs, Dr. Schlenker presented the historic evolution of heat tolerance using data from Indiana. He showed that while corn yields have increased continuously in the second half of the 19th century by a total factor of three, the evolution of heat sensitivity is highly nonlinear, growing with the adoption of double-cross hybrids in the 1940's, peaking around 1960, and then declining sharply as single-cross hybrids were adopted. However, Dr. Schlenker questioned whether future innovation could increase both yield and heat tolerance. He suggested that genetically modified crops may have the most potential.

Dr. Schlenker then discussed the role of agriculture and land use change in contributing to or mitigating climate change. He noted that land use change is responsible for approximately 20% of CO_2 emissions. Dr. Schlenker specifically discussed ethanol, which converts agricultural land from food production to energy production in an effort to mitigate climate change. He explained that the estimated food supply elasticity is roughly twice as large as the demand elasticity. As a result, one third of the caloric input diverted to biofuel production would be compensated with a reduction in food consumption while two thirds would be compensated with increases in food production. He noted that the U.S. ethanol mandate is predicted to lead to a decrease in food consumption of 1%, an increase in commodity prices of 20%, and a possible expansion of agricultural areas.

Discussion: Agriculture

During the discussion session, a couple of participants asked questions about CO_2 fertilization effects. One participant asked how CO_2 fertilization should be incorporated into reduced-form models, such as those used to develop the SCC. Dr. Rosenzweig explained that AGWIP would hopefully be able to isolate the CO_2 effects for incorporation. She expressed her belief that an average of current estimates is correct. She believes that the high- and low- (zero) ends of current estimates are both incorrect. Dr. Schlenker noted that there is a wide range of estimates found in the literature. Dr. Rosenzweig suggested that a risk management approach is most appropriate, where ranges and uncertainties are estimated and used, instead of a single number. Another participant asked whether CO_2 fertilization effects are non-linear and characterized by plateaus. Dr. Rosenzweig noted that there are bursts and ebbs in some processes but that effects continue up to concentrations of 700, and possibly even 800ppm.

One participant asked about the biophysical basis for climate change effects and whether biophysical barriers might pose a limit to adaptation efforts. Dr. Rosenzweig first outlined the biophysical effects of climate change, including temperature-caused speed up of the lifecycle, damage at critical growth periods, and water stress. She reiterated that the easiest adaptation efforts include management actions such as planting earlier. She noted that crop breeders are optimistic about the potential of genetic improvements, though there is not a lot of plasticity in the genes controlling for certain growth stages. Dr. Rosenzweig emphasized the challenge of pairing heat tolerance with high yields.

Another participant asked whether the speakers thought current estimates are optimistic (meaning incomes will likely be worse than predicted) or pessimistic, particularly considering the existence of known and unknown unknowns. Dr. Schlenker acknowledged that the unknowns pose a difficult question. Dr. Rosenzweig suggested current estimates may be overly optimistic. She emphasized the need for collaboration between climate scientists, agronomists, and economists. A different participant suggested the need for greater interaction between economic models and crop models. Dr. Rosenzweig agreed, noting that AGMIP facilitates a trans-disciplinary interaction and dialogue.

A final participant asked to what extent Dr. Schlenker's current statistical results could be used to improve IAMs. He noted the need to separate the effects of temperature, CO_2, and precipitation in IAMs. Dr. Schlenker emphasized the uncertainty in modeling precipitation, particularly extremes. He concluded that using currently available estimates of extreme precipitation would not necessarily improve agricultural impact estimates.

Sea Level Rise

The fifth session concluded Day 1 of the workshop and covered the impacts and damages from sea level rise. The session was moderated by Dr. Robert Kopp of DOE and included presentations by Dr. Robert Nicholls, University of Southampton; and Dr. Robert Tol, Economic and Social Research Institute.

Sea Level Impacts of Climate Change

Dr. Robert Nicholls of the School of Civil Engineering and the Environment and the Tyndall Centre for Climate Change Research at the University of Southampton introduced the last impact category of Day One, the sea-level impacts of climate change. Dr. Nicholls began by emphasizing the importance of sea level rise, despite the coasts being a small proportion of the earth's surface. He showed that population and economic density in the coastal zone is significantly greater than other areas of the earth's surface.

Next, Dr. Nicholls explained that climate-induced sea level rise is caused by the thermal expansion of seawater, as well as the melting of land-based ice (e.g., small glaciers in the Rockies or Alaska, the Greenland ice sheet, the West Antarctic ice sheet). He showed that sea level was fairly stable in the 19th century and that the rate of sea level rise has accelerated recently. He noted the great uncertainty regarding future projections of sea level rise.

Dr. Nicholls emphasized the importance of keeping climate change in context. While climate change is contributing to sea level rise, the coast is also experiencing other changes that contribute to changing sea level (e.g., coastal management, water extraction). Dr. Nicholls emphasized that relative sea level, which is determined by both sea level rise and subsidence, is what matters.

Dr. Nicholls then presented the impacts of sea level rise, which include: inundation, flood, and storm damage; wetland loss and change; erosion; saltwater intrusion; and higher water tables and impeded drainage. He noted that all five impacts are affected by interacting climate and non-climate factors. Dr. Nicholls next showed the links between sea level rise impacts and socio-economic sectors, noting the high number of strong links and lone potential benefit. Dr. Nicholls presented a series of images showing observed impacts from sea level rise (including its interaction with storms) and maps identifying the areas, cities, and assets exposed to future sea level rise.

Next, Dr. Nicholls presented a graph showing the limits of mitigation actions to control sea level rise. He emphasized the globe's current commitment to sea level rise, noting that mitigation efforts are only able to stabilize the *rate* of sea level rise. He emphasized that mitigation is still beneficial, while limited. He noted that the globe's commitment to sea level rise indicates a need for adaptation action.

Dr. Nicholls explained that adaptation can include (planned) retreat from the coasts, accommodation of assets (e.g., raising houses on stilts), and coastal protection using hard or soft barriers. Each impact is associated with multiple possible adaptation responses. He noted that, generally, the relative cost of adaptation is extremely low when compared to the coasts' value. Dr. Nicholls presented the optimistic and pessimistic views of potential impacts from and adaptation to sea level rise. He noted that both views are supported by reasonable arguments.

Dr. Nicholls finished with a series of concluding remarks, including the following. Climate-induced sea-level rise is inevitable; the major uncertainty is its magnitude. Climate-induced SLR will be compounded by subsidence in many densely-populated coastal areas. Risks are already increasing, and this will continue. The worst-case (do nothing) impacts are dramatic. There are widely differing views concerning the success or failure of adaptation. Mitigation of climate change and subsidence is needed to make the problem more manageable. To adapt to dynamic coastal risks, proactive assessment is required.

Following Dr. Nicholls' presentation, one participant suggested that sea level rise studies be combined with studies on storm length and intensity, citing the importance of winter storms in the Netherlands. Dr. Nicholls agreed and suggested that specific drivers and key issues need to be evaluated for each place on the earth's coast.

Estimating the Economic Impact of Sea Level Rise

Dr. Richard S. J. Tol of the Economic and Social Research Institute in Dublin, Trinity College in Dublin, and Vrije Universiteit in Amsterdam, continued the discussion of sea level rise by presenting the economic impact of sea level rise. Dr. Tol presented the economic implications of sea level rise, focusing on direct costs, adaptation, and general equilibrium effects.

Dr. Tol explained that, to estimate direct costs, economists typically estimate a unit cost and multiply the unit cost by the impact estimates provided by natural scientists such as Dr. Nicholls. For example, to estimate the costs of inundation, an economist would multiply the number of acres submerged by the average acre value. Dr. Tol emphasized that average acre values should be used as opposed to beach front values since property markets will adjust to coastal realignment. He noted the difficulty in estimating average acre cost, citing a study that used nonmarket valuation to identify wetland values.

Next, Dr. Tol emphasized the importance of incorporating adaptation into estimates of climate damages. He showed that populations with higher income generally suffer less and are less vulnerable to floods. However, he noted that even fairly sophisticated models are only able to explain 60 to 70 percent of vulnerability, due to a large amount of variation that is not understood. He noted that while optimal adaptation models can be built, historically, adaptation has never been optimally implemented. He showed numerous examples of suboptimal adaptation implementation, where adaptation efforts indicate an under- or over-valuation of damages, as estimated under the IPCC Special Report on Emissions Scenarios (SRES) A1B scenario. For example, the Dutch currently pay approximately 0.2% of GDP for coastal protection while damages are estimated to be less than 0.1% of GDP. One participant questioned the assumptions and results presented, questioning why Holland would be affected by the impacts from the SRES A1B scenario.

Finally, Dr. Tol presented general equilibrium effects of sea level rise. He explained that land loss would affect agriculture, and hence all other markets, and that coastal protection would affect construction and capital. He presented the results from a static computable general equilibrium (CGE) model, first with no protection and then with full protection. He noted that impacts only amount to fractions of a percent and that losing capital is more important than losing land. Dr. Tol emphasized that increases in GDP modeled under full protection are misleading since GDP is a measure of economic activity, not welfare. Instead, Dr. Tol suggested that, globally, direct costs are a reasonable measure of welfare costs.

Dr. Tol finished with a series of conclusions. He noted that sea level rise is one of the better understood impacts even though estimates contain significant uncertainty. He noted that the extent of saltwater intrusion, future storm characteristics, wetland value, and adaptation are some of the largest sources of uncertainties.

Discussion: Sea Level Rise

During the discussion session, several questions touched on the issue of timescales. One participant noted the contradictory conclusions about impacts from warming that have been generated in different studies. For example, politicians have identified 2°C of warming as problematic, FUND has identified net benefits up to 3°C of warming, and other studies indicate that the Greenland ice sheet would collapse with 3°C of warming. He noted that sea level rise is one of the biggest impacts on a long timescale. Dr. Tol clarified that SLR is not a large component of marginal impacts. He explained that the damages from SLR due to melting of the Greenland ice sheet would depend on the timescale of the melting. If complete melting occurred over two to three centuries, with sea level rising at three meters per century or more, it would be very difficult to adapt, causing significant damages. However, if the rate of sea level rise was two meters per century, it would be possible to raise dikes and adapt. He noted that rapid collapse of the West Antarctic Ice Sheet would cause many coastal cities to be largely flooded.

In response to another question, Dr. Nicholls emphasized the importance of evaluating the distribution of impacts over time, rather than focusing on expected annual damages. In particular, he noted the importance of events such as storms. He noted that while climate change may increase storms, storms drive coastal action today and the issues will be fundamentally the same in the future.

Another participant again raised the issue of interacting impacts, expressing his frustration that workshop discussions have focused on storms without sea level rise and sea level rise without storms. He emphasized the non-linear and interactive nature of climate change impacts. Dr. Tol noted that there are other interacting impacts as well, including changes in wind and sedimentation patterns.

Several questions addressed the impacts in the Netherlands. In response to one question, Dr. Tol explained that the Dutch are overprotecting against some predicted impacts. In fact, the speakers noted that the Dutch conducted an economic analysis intending to justify their work, but got results that indicated the work was not justified. In response to another question, Dr. Tol clarified that the Dutch are spending about twice as much as they would have in the absence of predicted sea level rise, to prepare defenses for 60-80 cm of SLR in the SRES A1B scenario. Dr. Nicholls noted that the SRES scenarios are optimistic.

The last group of questions concerned extreme storms. One participant asked the speakers to confirm that the Netherlands were building coastal infrastructure to withstand a 1 in 10,000 year event while New Orleans is building for a 1 in 100 year event. Dr. Nicholls explained that the new defenses in New Orleans are built for a 1 in 100 year event, but would probably withstand a 1 in 500 year event without breach. Another participant asked the speakers to confirm that SLR was not substantively included in rebuilding efforts after Hurricane Katrina. Dr. Nicholls confirmed that New Orleans may have done a little to include SLR, but for the most part, SLR was not included.

Marine Ecosystems and Resources

After brief Day 2 opening comments from Elizabeth Kopits, the sixth session commenced, covering the impacts and damages to marine ecosystems and resources. The session was moderated by Dr. Chris Moore of EPA and included presentations by Dr. Sarah Cooley, Woods Hole Oceanographic Institute; Dr. Paul McElhany, National Oceanic and Atmospheric Administration (NOAA); Dr. David Finnoff, University of Wyoming; and Dr. John Whitehead, Appalachian State University.

Modeling Climate and Ocean Acidification Impacts on Ocean Biogeochemistry

Dr. Sarah Cooley of the Woods Hole Oceanographic Institute initiated the discussion on marine ecosystems and resources by presenting an overview of modeling changes in ocean biogeochemistry due to ocean acidification and climate change. She organized her discussion into four sections.

First, Dr. Cooley presented an overview of the chemistry and observed impacts of ocean acidification. She explained that a quarter of the anthropogenic CO_2 burden dissolves in the ocean, combining with water to produce carbonic acid. She noted that the rate of present change in ocean acidification is too fast to be compensated by rock weathering and other mechanisms. Dr. Cooley presented a series of graphs that show increasing atmospheric CO_2 concentrations are associated with increasing ocean CO_2 concentrations, decreasing ocean pH, and decreasing saturation states for calcite and aragonite, which are used by marine animals to produce hard parts (e.g., shells). She also showed that anthropogenic CO_2 has penetrated to ocean depths of thousands of meters.

Dr. Cooley noted that ocean acidification is likely to cause other changes in ocean biogeochemistry. For example, nitrogen-fixing organisms such as phytoplankton thrive in the higher concentration of CO_2, likely causing a shift in the nitrogen pool towards ammonia. Additionally, changing pH and/or CO_2 concentration will likely change metal ion speciation, increasing both copper (which is toxic) and iron (which is a fertilizer). Dr. Cooley emphasized that ocean acidification is occurring along with numerous other anthropogenic stressors, which could be antagonistic or synergistic to acidification-induced change.

Second, Dr. Cooley discussed Earth system model simulations and their ability to predict future conditions. She noted the use of data-model comparisons to evaluate model skill. She explained that it is crucial to correctly model ocean physics and that biogeochemical parameterizations are under continuous improvement. Dr. Cooley explained the use of model intercomparisons to create and evaluate forecasts, including the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP). She explained that the most significant uncertainty in modeling ocean acidification is identifying future atmospheric CO_2 concentrations.

Third, Dr. Cooley discussed biological responses to ocean acidification. She identified numerous biological groups that will be directly or indirectly affected by ocean acidification, including corals, mollusks, plankton, reef communities, and marine predators. She demonstrated that calcification responses vary significantly among different organisms. She emphasized that individual, population, and ecological implications, including follow-on food web effects, are not yet understood. She presented evidence that calcifiers tend to vacate areas when conditions do not suit them.

Next, Dr. Cooley discussed the valuation of ecosystem services. She noted that most studies focus on market values, but that non-market values, indirect use values, and non-use values must also be incorporated in an informed analysis. She presented an estimate of damages assuming that decreases in pH result in lower mollusk harvests. She estimated annual losses of $75 to $187 million in ex-vessel revenues from a 0.1 to 0.2 pH decrease, amounting to $1.7 to $10 billion in net present value losses through 2060. Dr. Cooley noted that valuation of impacts on coral reefs is driven by tourism effects.

Fourth and last, Dr. Cooley discussed knowledge gaps and needs. She noted the need to properly link three main models: physical, biological, and human/economic. She identified numerous relationships within these models that are not well understood. Finally, Dr. Cooley presented the increasing level of uncertainty associated with the progressing stages of ocean acidification impacts (e.g., changes in ocean pH are more certain than effects on marine organisms, which are more certain than changes in ecosystem services).

In response to a question, Dr. Cooley explained that there are a large number of studies examining the observed impacts of historic ocean acidification. However, she explained that there are no good baselines to ascertain when “normal” conditions are exceeded. She noted that numerous time series stations are currently examining this question, which is high on the international research agenda.

Modeling Climate and Acidification Impacts on Fisheries and Aquaculture

Dr. Paul McElhany of the NOAA Northwest Fisheries Science Center expanded on Dr. Cooley’s presentation with a discussion of modeling climate change and acidification impacts on fisheries, aquaculture, and other marine resources.

Dr. McElhany started by enumerating the impacts and impacted resources associated with climate change and ocean acidification. He noted that impacts on capture fisheries will be complicated, while aquaculture has some ability to adapt using relocation, control, and species switching. He further noted that while the direct CO_2 effects on growth and survival are relatively well understood, the effects on stratification and circulation are not known.

Next, Dr. McElhany described nearly a dozen different model types that are used to model impacts on marine resources, including: fishery stock assessments, population viability analyses, food web/ecosystem models, NPZ (nutrients, phytoplankton, zooplankton) models, minimum realistic models, maximum unrealistic models, modeled range maps, individually-based models, life-cycle models, bioenergetics, and expert systems. Dr. McElhany noted that IPCC-class Earth system models must be downscaled to match the near-shore, small-scale processes at the biological scale. He noted that the IPCC avoided modeling coastal ocean impacts due to their complexity. However, he emphasized that biological action is concentrated in coastal regions and that these gaps must be addressed.

Dr. McElhany then presented several examples of marine resources modeling. His examples spanned a wide range of scale and scope. Some examples only examined a single variable or a single species, while other examples examined all climate change impacts or entire ecosystems. Dr. McElhany noted the vast complexities associated with the life cycle of a single species and the greater complexities associated with ecosystems. He emphasized the importance of modeling interactions between species. He highlighted one study’s results that indicate a general decline in fisheries, especially with all climate change effects, and that range shifts will be the biggest impact. He noted the ambitious nature of the Atlantis model which attempts to couple oceanography, ecology, and fisheries submodels. He also noted a fairly comprehensive evaluation of fisheries using a bioclimate envelope.

Dr. McElhany provided a “reality check” that identified numerous big questions remaining regarding marine resources. He identified significant unknowns including changes in the Gulf Stream, stratification, upwelling, and decadal oscillations, among others. He noted the possibility for positive changes, such as improved fishing in some areas. Dr. McElhany further noted that details are critical in modeling marine resources. For example, species interactions, phenology, synergistic effects, short-term variability, and local circulation are all critical factors. He noted that lab studies do not necessarily scale to ecosystems.

Finally, Dr. McElhany suggested that coarse-scale impact assessment would be beneficial in the future. He suggested the use of back-of-the-envelope estimates and assessment using three approaches: a bioclimate envelope to provide key first pass estimates, minimum realistic models, which model only the most important components of a specific system, on high value fisheries, and ecosystem and food webs to look for interactions. He emphasized the importance of resolving the big climate questions.

In response to a question, Dr. McElhany noted that he was not aware of any studies examining the effects of changing aragonite saturation states on fish. He noted one observational study that indicates major oyster reproductive failures in the past several years, which are correlated to pH changes. A different participant suggested that the reference case for marine resources needs to be carefully considered and that acidification impacts need to be considered in the context of a variety of other environmental stressors that affect the baseline.

Economic Impact of Climate Change and Ocean Acidification on Fisheries

Following Dr. McElhany's presentation, Dr. David Finnoff of the University of Wyoming commenced the economic portion of the marine resources discussion, with his presentation on the economic impact of climate change and ocean acidification on fisheries. Dr. Finnoff began by describing the potential significance of ocean acidification, citing historic mass extinction events linked to ocean surface pH, challenges for calcifying organisms, and Dr. Cooley's work that calculated net present value losses from decreased mollusk harvests of $1.7 to $10 billion through 2060. He noted that Dr. Cooley's work, while providing a useful initial estimate, is based on lost revenue rather than more appropriate measures of welfare such as consumer surplus.

Next, Dr. Finnoff discussed the economic consequences of ocean acidification, noting that disruptions in ecosystem services are material damages that imply welfare changes. He highlighted the reciprocity of the relationship where ocean acidification is caused by human activity and, in turn, affects human activity. Dr. Finnoff explained that assessment of material damage requires characterizing the changes in production and consumption, determining the responses of prices, and identifying adaptation options. He noted that changes in ocean acidification do have the potential to affect production possibilities, as well as direct and indirect costs.

Dr. Finnoff explained that both reduced-form/partial equilibrium and structural/general equilibrium representations have pros and cons. He emphasized the importance of identifying the appropriate balance and utilizing both approaches. He explained that non-convexities and species interaction require more detailed and comprehensive models. Through a series of simplified graphs, he demonstrated that with problems characterized by non-convexity, it is necessary to understand the entire surface of possibilities to be able to locate the global optimum.

Using an illustrative example of the Bering Sea Food Web, he discussed a simplified model that might be used in an IAM. He demonstrated the non-linear, non-systematic results from shocks, and identified non-convexities, non-monotonic changes, and problems with reduced-form aggregation. He concluded that bio-economic harvests of fish and crab are likely affected to varying degrees and magnitudes depending on their location in the food web; non-harvested stocks may or may not have cascading effects depending on their location in the food web; and to assess tradeoffs, it is necessary to assess changes in flows and stocks simultaneously.

Dr. Finnoff concluded that welfare measurement of materials damages has some well-known characteristics, but that for ocean acidification, a lot of issues remain unresolved. He suggested that a clear understanding is needed of how ocean acidification affects production and consumption possibilities in a consistent setting. He noted that using dose-response relationships of environmental change from the natural sciences is crucial, but that it is not yet resolved how much detail is necessary for a good understanding. Finally, Dr. Finnoff concluded that if problems are convex or well-behaved, aggregate representations of the natural science may be sufficient for good economic assessments. However, if problems have pervasive non-convexities, he noted that policy makers must expand the scope of their analysis for good economic assessments. It may be necessary for the assessor to know the entire possibilities surface.

Nonmarket Valuation of Climate and Acidification Impacts on Marine Resources

Dr. John Whitehead of Appalachian State University delivered the final presentation in the marine ecosystems and resources impact category. He described nonmarket valuation of climate change and ocean acidification impacts to marine resources.

Using the example of coral reefs, Dr. Whitehead described the different methods available to estimate nonmarket values. He explained that use values may be estimated by the willingness to avoid climate change due to use of affected resources. Direct uses of coral reefs include diving, snorkeling, and viewing; indirect uses include fishing. He then explained that non-use, or passive use, values may be estimated by the willingness to avoid climate change without the intent to use the affected resources. Willingness to pay for nonuse values can be motivated by altruism, ecological ethic, or bequests.

Dr. Whitehead explained that use values can be estimated using revealed preference or stated preference valuation methods, while non-use values can only be estimated using stated preference methods. Dr. Whitehead further explained that revealed preference methods include hedonic price, averting behavior, and travel cost methods, as well as producer surplus values. He noted that the travel cost method is most appropriate when considering marine resources. Dr. Whitehead then described stated preference methods, which include contingent valuation, choice experiments, and contingent behavior. He explained that there are problems with both revealed preference and stated preference methods, which can be mitigated by joint estimation of revealed preference and stated preference data.

Dr. Whitehead cited several examples in the climate change literature of revealed preference and stated preference studies. He explained that no study to date explicitly addresses nonmarket valuation of climate change and marine resources. Instead, Dr. Whitehead discussed a very simple nonmarket valuation based on data from national recreation surveys, where he regressed saltwater fishing participation and fishing days on temperature and precipitation. He suggested a more complex estimation would be possible using the recreational fisheries demand study.

Dr. Whitehead concluded that there is very little existing research with which to develop the SCC for marine resources. He suggested that meta-analyses could be used in a benefit transfer study, using values for coral reef recreation, outdoor recreation, and recreational catch. However, he noted that the behavioral response to climate change is missing. Dr. Whitehead suggested that a wide variety of studies is needed, using both revealed and stated preferences, to estimate total economic value, use value, and non-use value. He suggested the most promising avenue is using existing revealed preference data. New studies using stated preference data could differentiate between marine and other values and estimate the behavioral response to climate change. Revealed preference and stated preference joint estimation could differentiate between use and non-use value.

Discussion: Marine Ecosystems and Resources

During the question and answer session, one participant asked how changes in keystone species can be incorporated in food web models. Dr. McElhany suggested that if food web models are built properly, keystone species should be included. He noted that model results become more tenuous as conditions change further away from the case in which the model was parameterized.

A second participant questioned the incorporation of thresholds and discontinuities into economic models. He noted that economic models indicate small marginal changes, but that natural scientists tend not to consider marginal changes, as they are more concerned with thresholds. Dr. Finnoff agreed about the importance of thresholds and discontinuities, emphasizing the aspects of his presentation that dealt with non-linearities. Dr. Finnoff explained that the economics literature knows how to handle thresholds, in principle. He suggested the need for an approach to evaluate the proximity of thresholds. He suggested using a recursive view and developing a model that can handle changes in states. Dr. Whitehead added that there is a need for non-use values in a world very different from today. He suggested the possibility that entire classes of opportunities could disappear. He noted the need for modeling to address individuals' recreational choices. Dr. McElhany cited large scale ecological changes in the North Pacific as a historical example of state changes that resulted in big community changes.

A third participant asked if the rate of ocean carbon uptake is constant or changing. Dr. Cooley noted recent efforts to evaluate the ocean's ability to take up CO_2 in the long run. She cited evidence that ocean uptake is slowing and will continue to slow due to chemical reasons and changes in ocean circulation. She noted that the slow-down will not reverse or even significantly alleviate ocean acidification.

Several participants asked about the interactions between different stressors. One participant asked about climate change impacts other than ocean acidification, such as loss of phytoplankton biomass. Dr. McElhany explained that the results he presented were based on a model generation previous to newer data on changes in primary productivity. He emphasized there is ongoing and continued learning, as well as remaining unknowns including changes in primary productivity, in ocean circulation, in temperature regimes, in stratification, and in availability of nutrients. He noted that each unknown could have significant effects.

Another participant asked if productive areas of the ocean would be squeezed as warming-induced range shifts move commercially valuable species pole-ward and ocean acidification pushes some species toward the equator since ocean acidification happens more rapidly in colder water. Dr. McElhany agreed that might happen, noting a lack of study on the interacting trends. Dr. Cooley agreed with the participant's summary, noting the need to do lab experiments to better understand the interacting effects.

A different participant asked whether coral reefs would be able to adapt to sea level rise by growing towards the sun and whether ocean acidification would affect their ability to adapt. Dr. Cooley noted that coral reefs can grow annually by millimeters or centimeters. However, she noted several interacting factors that might impede the ability of corals to adapt, including the change in deep ocean chemical conditions and the vertical and latitudinal shrinking of optimal waters. She explained that these interactions are not well understood. She further noted that coral growth rates do not necessarily correlate with vertical growth, due to the somewhat horizontal structure of corals.

A final participant asked about incorporating coral bleaching into IAMs. He noted that coral bleaching is tied to warming and is an example of a non-linear, non-marginal impact. Dr. Cooley agreed with the need to incorporate coral bleaching, disease, and destruction. She suggested that research on ocean acidification is a necessary first step, since it is necessary to understand acidification before it is possible to understand synergistic interactions. She further noted that ecosystem-scale studies are time- and manpower-intensive, and expensive, resulting in a small number of existing studies. Dr. Whitehead added that revealed preference studies would not address coral bleaching well, but that stated preference studies could. Dr. Finnoff noted economic studies on previous large scale disasters might be informative to this issue.

Terrestrial Ecosystems and Forestry

The seventh session covered the impacts and damages to terrestrial ecosystems and forestry. The session was moderated by Dr. Steve Newbold of EPA and included presentations by Dr. Karen Carney, Stratus Consulting; Dr. Brent Sohngen, Ohio State University; and Dr. Alan Krupnick, Resources for the Future.

Biological Responses of Terrestrial Ecosystems to Climate Change

Dr. Karen Carney of Stratus Consulting started the terrestrial ecosystems and forestry discussion by presenting the impact of climate change on terrestrial ecosystems. She noted that her presentation was not meant to be comprehensive, instead aimed at highlighting some key impacts and related tools.

Dr. Carney described how terrestrial ecosystems provide numerous economically important services: the provisioning of food, water, and raw materials (e.g., timber, non-timber forest products); regulation of air quality, storm protection, and waste assimilation; and cultural services such as recreation and passive use value. She noted that climate change will fundamentally and potentially dramatically affect the location and character of today's ecosystems. She noted key changes including changes in species locations, ecosystem productivity, rates of ecosystem processes, and disturbance regimes (e.g., drought, fire, pest outbreaks).

Next, Dr. Carney discussed three major ecosystem impacts—changes in vegetation distribution and dynamics, wildfire dynamics, and species extinction risks—that have the potential to be included in IAMs. She selected these impacts as they best met the following criteria: ecological importance, economic importance, and being well understood. For each of the three impacts, Dr. Carney discussed why the impact is likely to occur, the tools available to estimate the impact, what research has shown, key uncertainties or other shortcomings with projecting future impacts, and what key services are likely to be affected.

Dr. Carney noted that changes in vegetation distribution and dynamics, which will be affected across the globe, are most commonly examined using dynamic global vegetation models (DGVMs). She noted that there are many DGVMs available that can examine multiple scales (e.g., countries, regions, globe). Most DGVMs consist of interacting biogeography, biogeochemistry, and fire modules. She highlighted a couple of studies using DGVMs, one which examined vegetation changes in the United States and a second which examined changes in global tree cover. She emphasized that both studies predict fundamental and large-scale changes. Dr. Carney explained the limitations of DGVMs, including that there is a significant amount of variability across models for the same region and climate scenario, with results highly dependent on the GCM used. She noted additional limitations, including an absence of most other anthropogenic factors, the assumption of no barriers to plant dispersal, and an absence of pest and pathogenic influence. She noted that there are some general areas of agreement between models and that scientists should look for these areas, perhaps averaging DGVM results, when possible.

Next, Dr. Carney explained that climate change will affect wildfire dynamics through direct (e.g., higher temperatures, dryer fuels) and indirect (e.g., changes in vegetation type) mechanisms. She noted that wildfire dynamics can be modeled using statistical models based on historic fire behavior, as well as using the fire module of DGVMs. Dr. Carney presented the results of one study that predicts decreased fire in northern Canada and Russia, and increased fire in the United States, central South America, southern Africa, western China, and Australia. She explained that wildfire models can only roughly approximate both historic and future wildfire dynamics, and that they are unable to predict the timing and location of specific fires.

Finally, Dr. Carney discussed species extinctions, which are most commonly modeled using climate envelope models. These models use current distributions of a species to construct climatic requirements and then determine where species could live under future climate conditions. She noted that extinctions are likely to occur, but that the results of these studies vary widely, with predicted extinctions ranging from relatively low levels up to 60% of species. She noted several key uncertainties in climate envelope models, including: that species may be flexible and able to survive in a wider range of climate conditions than is predicted by their current range, that biotic interactions may be more important than climate in determining species range, that dispersal is likely limited by habitat fragmentation, and that land use change may amplify climate change impacts. She further noted that is difficult to value global biodiversity and that economic value is often tied to specific species or locations rather than global extinctions.

Dr. Carney concluded with recommendations for future research needs. She suggested that methods need to be developed to integrate results across studies and tools (e.g., meta-analyses, ensemble means). She suggested a major need to develop large-scale, long term projections for changes in pest outbreaks and interior wetland change and loss. She also noted the importance of understanding changes in snow pack, particularly as related to ecosystems and recreation.

Estimating the Economic Impact of Climate Change on Forestry

After Dr. Carney's presentation, Dr. Brent Sohngen of the Department of Agricultural, Environmental, and Development Economics at Ohio State University and a University Fellow for Resources for the Future, presented on estimating the economic impact of climate change on forestry.

First Dr. Sohngen described the general process of measuring damages, which starts with future climate scenarios and concludes with economic impacts. He noted that feedbacks and interactions between different steps of the analysis are important and require additional research. Dr. Sohngen then explained that both models and observations indicate increases in productivity due to: CO_2 fertilization, warming in colder climates, and precipitation gains where water is limited. He noted that DGVMs indicate limits to productivity gains and suggest ecosystems will change from a carbon sink to a carbon source within the next several decades.

Dr. Sohngen presented results in the literature that predict a reduction in total U.S. ecosystem carbon, with losses greatest in the eastern United States and under more recent climate scenarios. Without accounting for adaptation, these ecosystem effects could result in emissions of up to 500 million t C per year and a total loss over the century of 10-20 billion t C. He then presented regional estimates from the literature on timber market results. He showed that timber output and consumer surplus is expected to increase in almost all regions, but that producer returns only increase in about half of the regions.

Dr. Sohngen then presented preliminary results from an analysis that is currently underway. That study incorporates several key factors into the economic analysis, including yield change, stock losses, and area suitable for trees. It also incorporates adaptation options, including existing stock management by changing rotations and salvage; replanting of new species if growing and economic conditions warrant it; and future stock management by changing rotations, management, and investments. He showed that that global output is expected to increase by 5-15% while global prices are expected to decrease by 5-15%.

He explained that regional results suggest that there will be winners and losers, but that the allocation of benefits and losses depend on the climate scenarios. He noted that Brazil, Canada, Russia, and Oceania are likely to experience net benefits. Finally, he emphasized that the management of forest stocks will be complicated by disturbance. He noted that large-scale disturbances are already influencing outputs in many regions (e.g., mountain pine beetle outbreaks in Canada, forest fires in Russia) and that disturbance patterns are expected to change with climate change. He noted that increases in productivity are not expected to be able to counter falling global prices.

Dr. Sohngen concluded by describing some of the study's limitations. He noted that timber markets may not be most important demand on forestland in the future, that models are deterministic, and that ecosystem models are calibrated without human influences. After the conclusion of his presentation, Dr. Carney asked if crop shifting is incorporated into his model. She noted that if timber prices drop too low, people may decide to use the land in other ways. Dr. Sohngen explained that this type of crop shifting is partially incorporated.

Valuing Climate-associated Changes in Terrestrial Ecosystems and Ecosystem Services

Dr. Alan Krupnick provided the third and last presentation for the terrestrial ecosystems and forestry impact category, on valuing the impacts of climate change on terrestrial ecosystem services. Dr. Krupnick focused his comments on non-use values and stated preference studies. He noted that even a low WTP per person can amount to significant totals.

Dr. Krupnick discussed the transition from natural science assessment to economic assessment, where biophysical endpoints estimated by natural scientists are used as the starting points in valuation studies. He explained a need for natural scientists to provide biophysical impacts assessment endpoints that correspond to the items assessed in valuation exercises (valuation starting points), that people value and care about, and that have functional relationships with climate drivers. He explained a parallel need for economists to develop a consensus approach to classify endpoints to be used as valuation starting points. He noted that natural scientists have identified large numbers of climate change impacts, from which endpoints need to be identified. He further noted that economists have not been able to easily define the things that matter from an economic perspective.

Dr. Krupnick explained that, when conducting stated preference studies, it is crucial to ask the right questions. He noted that survey respondents should be asked to value biophysical outputs (e.g., number of eagles), rather than biophysical inputs (e.g., number of acres of eagle habitat). He explained that natural scientists should identify the production function that defines the relationship between inputs and outputs. He also noted that it may be better to not mention climate change, particularly in U.S. studies, as climate skeptics might provide biased answers. He questioned how best to admit uncertainties in surveys without inducing protest bids.

Dr. Krupnick presented several examples of stated preference surveys where survey respondents are given a set of options to choose from with a suite of associated conditions. He noted one study that suggests the household monthly mean WTP for a 30% greenhouse gas reduction is $22 in Sweden, $17 in the United States, and $5 in China.

Dr. Krupnick classified starting points for climate change into four categories: use values; "standard" non-use values; combinations associated with events or broad scale changes; and novel changes. He then classified valuation studies into four categories: studies valuing relevant commodities in a non-climate context; studies transferring non-climate values to a climate change context; studies directly valuing relevant commodities in a climate change context; and stated preference top-down studies.

Dr. Krupnick went on to summarize and classify the literature using his set of starting points and survey types. Dr. Krupnick noted that there is a broad range of existing studies falling into almost every combination of startpoint and survey type. He suggested these studies provide a lot of material for meta-analyses and benefit-transfer. Dr. Krupnick noted the studies range widely in their spatial scale, but that spatial specificity enhances credibility. He highlighted that scope sensitivity tests ensure WTP is greater for avoiding larger damages or gaining larger benefits and that marginal returns decrease. He noted that existing studies suggest timing of benefits is not significant, implying low or zero discount rates. He explained that most studies assume certainty and very few vary uncertainty.

Dr. Krupnick noted that existing "non-climate" studies are useful but limited, that benefits transfers studies are artificial and assumption-based, and that climate-driven studies are useful and growing in number, but that they will always be location-specific and thus patchy. He noted that top-down studies are tempting as they provide a broad coverage of endpoints and locations, but that they involve highly imprecise commodity definitions and scenarios. He highlighted a need for holistic valuation estimates.

Discussion: Terrestrial Ecosystems and Forestry

After Dr. Krupnick's presentation, the terrestrial ecosystems and forestry discussion session commenced. One participant noted the finding highlighted by Dr. Sohngen that forest productivity would increase due to climate change. Since forests provide an important low-cost mitigation option, she asked how this trend could be incorporated into mitigation costs in the SCC. Dr. Sohngen noted that initial unpublished models suggest lower costs of carbon sequestration, but that it is a broad, uncertain result.

Several participants and speakers discussed the usefulness of the concept of ecosystem services. Dr. Krupnick expressed satisfaction that the concept had gained traction, as it does provide a bridge into the economic sphere by using the term 'service'. However, he suggested it was only a starting point that only partially overlaps with important endpoints lying underneath the services. Another participant suggested that the literature does not provide good information on how climate change will impact ecosystem services. He agreed with Dr. Krupnick that the concept has potential and begins to provide a useful bridge. However, he suggested the concept had not gotten a lot of traction in policy making. He suggested that the concept should continue to be pursued in a sensible way. Dr. Sohngen agreed with the previous assessments. He added that the economic drivers for management and adaptation of timber markers seem to be decreasing, suggesting it is more compelling to consider their ecosystem services. Dr. Carney suggested that the concept of ecosystem services, while perhaps imperfect, is still useful. She explained that ecosystem services provide a way to translate ecological effects into changes that are important to individuals in a policy context.

Another series of comments focused on the language of stated preference surveys. Dr. Krupnick explained that a tax is frequently used as a vehicle in surveys but that the standard practice is to try to present a hypothetical real choice that has real costs. He emphasized that stated preference studies are not attitude surveys, and that responses should be limited by income and choices should be binding. He noted that surveys are aimed at estimating the individual willingness to pay. He added that studies are constructed to eliminate the possibility of "free riding" and to incorporate the effect that one individual paying in the absence of other contributions would have no effect.

In response to a final question, Dr. Sohngen explained that models do, at least partially, incorporate country variables (e.g., poverty) as timber production shifts across political borders. He explained that models incorporate different production costs (e.g., labor costs), management structures, species uses, and prices. He suggested the extent of incorporation may not be sufficient or perfect.

Energy Production and Consumption

The eighth session covered the impacts and damages to energy production and consumption. The session was moderated by Dr. Stephanie Waldhoff of EPA and included presentations by Dr. Howard Gruenspecht, U.S. Energy Information Administration; and Dr. Jayant Sathaye, Lawrence Berkeley National Laboratory (LBNL).

U.S. Energy Production and Consumption Impacts of Climate Change

As the first speaker for the Energy Production and Consumption Impact Category, Dr. Howard Gruenspecht of the U.S. Energy Information Administration discussed the energy system impacts of climate change. He noted that climate change impacts on energy systems have received considerable attention, despite high-profile reports finding that the impacts will be modest.

First, Dr. Gruenspecht presented climate change impacts on energy demand for space heating and cooling. He noted that the United States is a relatively cold country, where the amount of energy used for heating is three to four times as great as the amount used for cooling. He noted that this gap is even greater in other industrialized countries. He further noted that energy use for space conditioning is highly tied to development. Dr. Gruenspecht explained that the details of warming are very important in considering energy impacts. This includes the latitudinal, diurnal, and seasonal gradients. He explained that space conditioning is subject to thresholds and that measures of comfort produce very different impact estimates than measures of energy expenditures. Finally, Dr. Gruenspecht noted the importance of incorporating technology changes over relevant time horizons. Historic increases in cooling efficiency had significant impacts, and new technologies such as smart grid will likely have similar impacts.

Dr. Gruenspecht noted that the literature has focused on energy demands for space conditioning but that other areas of energy demand merit additional attention. He highlighted the energy-water nexus, since climate change stresses traditional water sources. He showed that non-traditional sources such as desalinized water require significant amounts of energy.

Next, Dr. Gruenspecht presented climate change impacts on energy supply. He noted impacts on access to traditional resources, including hydroelectricity's sensitivity to melting glaciers and arctic oil infrastructure's sensitivity to melting permafrost. He further noted the need for cool water and air to maintain power plant operation. However, Dr. Gruenspecht emphasized his feeling that too much attention has been placed on energy issues, which may not be quantitatively important in overall effects, particularly after mitigation and adaptation are considered.

Finally, Dr. Gruenspecht discussed the impacts of climate change on non-traditional energy sources. He noted the very significant effects of cloud cover and aerosols on solar power, the unclear changes in wind patterns that will affect wind power, and the agricultural effects on biomass.

Dr. Gruenspecht concluded that energy impacts may be beneficial for small to modest climate change, but dominated by negative impacts in the long-run. He emphasized that details are crucial in modeling impacts and that changes must be considered in the context of adaptation and technology change. He suggested the importance of distinguishing between energy system impacts, which are important to energy planners, and energy-system-related welfare impacts, which are important for cost-benefit analysis of climate change policies.

Impacts of Climate Change on Global Energy Production and Consumption

Following Dr. Gruenspecht, Dr. Jayant Sathaye of LBNL presented the impacts of climate change on global energy production and consumption. He started by presenting a list of over a dozen hydro-meteorological and climate parameters that each have numerous effects on energy demand and supply.

Dr. Sathaye then presented a selected review of international impact analyses in the literature. He noted that most of the literature focuses on energy demand, as opposed to energy supply. The literature indicates that global reductions in energy demand for heating will be greater than global increases in energy demand for cooling. For example, the POLES model estimates 200-300 million tons of oil equivalent (Mtoe)reductions in heating demand compared to 60-130 Mtoe increases in cooling demand. The literature indicates that global nuclear generation will decline, while hydroelectricity generation may increase or decrease depending on the scenario (more likely increase). Dr. Sathaye also presented examples of international studies at the national and regional scale.

Next, Dr. Sathaye presented an example of a study conducted in California to demonstrate the data and information needed to conduct an energy impact analysis. He explained that the study, funded by the California Energy Commission, focuses primarily on three impacts: increased temperature impacts on electricity capacity and demand; sea level rise impacts on energy infrastructure; and wildfire impacts on energy infrastructure. He presented the intricate flow chart of analysis stages, commencing with AOGCM emission scenarios and culminating in a summary of damages.

Dr. Sathaye then presented results from the study. He explained that warming temperatures may lead to both losses of up to 4,000 megawatts (4%) of available natural gas-fired power plant capacity, as well as increases in peak load cooling demand of 20%. He noted that the combined effect of changes in demand and supply result in a 24% gap between energy supply and demand that needs to be addressed.

Dr. Sathaye presented the maps of the wildfire analysis, which involved identifying the climate factors affecting wildfires, overlaying transmission lines on near-term and long-term spatial models of wildfire probability, and quantifying the length of transmission lines exposed to wildfires under modeled future climate scenarios. Dr. Sathaye explained a similar analysis for sea level rise, which concluded that a 1.4 meter projected rise in sea levels would affect 25 power plants and approximately 90 substations.

Dr. Sathaye concluded that there is a general lack of quantitatively-based impacts information for the energy sector, but that the base of international literature is growing. He reiterated global projections of larger decreases in heating demand compared to increases in cooling demand. He noted that the temperature impact on demand is much higher than on supply infrastructure and that the impact of wildfires could potentially be significantly high. Finally, he suggested that more data and research are needed to evaluate wildfire and sea level rise impacts on power sector infrastructure and temperature impacts on electricity transmission and distribution.

Discussion: Energy Production and Consumption

During the question and answer session, one participant again raised the need to incorporate interactions and double-counting across sectors, highlighting the intersection of health impacts driven by temperature with impacts on cooling demand. Another participant noted that an impact in one sector might be an adaptation in another. Dr. Gruenspecht added that there are significant impacts from adaptation, technology, and efficiency that must be considered. Dr. Sathaye agreed, noting the need to develop a long-term scenario of future infrastructure possibilities and combine that scenario with climate data.

Another participant asked how cooling penetrates lower socio-economic classes, noting that middle class and poor country adoption of cooling greatly determines international impact. Dr. Sathaye agreed with the importance of these effects. He noted that the air conditioning load in India has been increasing annually by 25%. He suggested that similar changes are occurring elsewhere in developing countries.

A third participant asked about distinguishing between costs of damages and costs of reducing risks, noting that the costs of reducing risks are often significantly lower than costs of damages. Dr. Sathaye agreed that this distinction is critical and should be reflected in the cost analysis. Dr. Gruenspecht also agreed, emphasizing that the future must be considered in the context of technology change. He acknowledged the extreme difficulty in attempting to predict the 100 year future, but emphasized its necessity.

During the discussion session, both speakers emphasized a need for more and better climate data, noting the need for information on things like cloud cover. One participant suggested that economists need to move forward with the data available now, since some aspects of physical climate change are going to be difficult to estimate more accurately anytime soon. Dr. Gruenspecht acknowledged the validity of her point but suggested that there is a middle ground where climate scientists might be able to provide more than what is provided now, but not everything desired by economists. For example, he suggested it would be helpful to have information on cloud cover on a global average scale. Dr. Sathaye agreed, noting that global average numbers provide a sense of the underlying information. Another participant argued that global average numbers are enormously insufficient and could do more harm than good when considering spatially specific investments and activities related to cloud cover and wind patterns. Yet another participant challenged the community to do better. The first participant suggested that economists need to lower their expectations. She explained that global average cloud cover is the greatest uncertainty in models. She suggested a need to make decisions under uncertainty. Another participant suggested it would be helpful to put bounds on the uncertainty with factors such as this.

Finally, one participant asked if heat waves and blackouts are incorporated in models. One of Dr. Sathaye's colleagues explained that the California study did incorporate the effect of heat waves, but did not include the costs of blackouts. The participant suggested that this would affect the overall conclusion related to heating and cooling demand. Dr. Gruenspecht reemphasized the distinction between energy impacts and welfare impacts.

Socio-economic and Geopolitical Impacts

The ninth session covered the socio-economic and geopolitical impacts and damages. The session was moderated by Dr. Alex Marten of EPA and included presentations by Dr. Nils Petter Gleditsch, Peace Research Institute Oslo; and Dr. Robert McLeman, University of Ottawa.

Regional Conflict and Climate Change

Dr. Nils Petter Gleditsch of the Centre for the Study of Civil War, the Peace Research Institute Oslo, and the Department of Sociology and Political Science at the Norwegian University of Science and Technology commenced the last impact session with his presentation on regional conflict and climate change. Dr. Gleditsch is an expert on conflict. During his presentation and through his abstract, Dr. Gleditsch indicated that the policy debate is running well ahead of its academic foundation, and sometimes even contrary to the best evidence.

First, Dr. Gleditsch presented current trends in armed conflicts and number of deaths. He explained that the world is moving towards a liberal peace – as democracy and trade increase worldwide, conflict becomes less likely. This movement includes increases in the number of international governmental organizations (IGOs), in democracy, in wealth, and in trade. He noted four possible threats to the liberal peace: shifting patterns of power, the financial crisis, fundamentalist religion, and climate change. He noted that climate change is arguably the most serious threat, highlighting numerous statements from non-governmental organizations, politicians, and some academics indicating climate change is a major issue that will greatly impact conflict. Despite the rhetoric, however, there is little systematic evidence to date that long-term climate change or short-term climate variability has had any observable effects on the pattern of conflict at any level. Dr. Gleditsch then presented a flowchart from the World Bank that presents numerous possible pathways that lead from climate change to conflict. He showed that natural disasters, migration caused by sea level rise or other climate factors, and increasing resource scarcity may all promote conflict.

Next, Dr. Gleditsch presented numerous, sometimes contradictory, findings from the literature regarding the influence of climate factors on conflict. To date there is little published systematic research on the security implications of climate change. The few studies that do exist are inconclusive, most often finding no effect or only a low effect of climate variability and climate change. The scenarios summarized by the Inter-Governmental Panel on Climate Change (IPCC) are much less certain in terms of the social implications than the conclusions about the physical implications of climate change, and the few statements on the security implications found in the IPCC reports are largely based on outdated or irrelevant sources.

Dr. Gleditsch presented evidence regarding the effects of precipitation, temperature, sea level change, and natural disasters. He noted that millions of people may become refugees due to sea level rise. He also noted that natural disasters may reduce conflict as people tend to unite in the face of adversity. Dr. Gleditsch discussed the economic effects of climate change, noting that economic factors are important in conflict. He explained that economic interdependence and economic development limit inter- and intra-state conflict, respectively; but that economic decline could reverse this.

Dr. Gleditsch presented arguments and counterarguments for several climate change impacts on interstate conflict. He suggested increased scarcity may or may not lead to interstate conflict. He also explained that climate change will open up new trade routes and new ocean territories. He noted that uncertainty about ownership and competition for exploiting these resources may or may not promote conflict. He suggested that climate change may affect where nations fight, rather than whether or when.

Dr. Gleditsch described methods analyzing the scarcity theorem, highlighting several criticisms of past studies. He highlighted the interactions of climate change with other factors, such as poverty, poor governance, and ethnic dominance, suggesting that climate change may act as a threat multiplier and destabilize conflict-prone regions. He suggested that, from a policy perspective, it is useful to examine whether it is easier to reduce climate change or other factors in the interaction. Dr. Gleditsch presented a map of the distribution of armed conflict, highlighting Africa, East Asia, and Central and South Asia as particularly vulnerable regions.

Finally, Dr. Gleditsch presented a list of research priorities. He suggested that future research needs to look at interactions between climate change and political and economic factors, to focus on countries with low adaptive capacity, to examine a broader set of conflicts, to conduct disaggregated studies of geo-referenced data, to balance negative and positive effects of climate change, and possibly to couple models of climate change to models of conflict. Dr. Gleditsch suggested that if climate change has negligible impacts on conflict, it matters significantly for the credibility of climate change research, very little for mitigation, and possible a lot for adaptation.

After the conclusion of his presentation, Dr. Gleditsch agreed with one participant's concern that studies of historic conflict may not inform the effects of unprecedented changes in climate. Another participant asked if there was evidence for conflict in small islands, which are particularly vulnerable to sea level rise. Dr. Gleditsch explained that there is not a lot of conflict in those areas, and that migration and security concerns will more likely result from climate change, than conflict.

Migration Impacts of Climate Change

Following Dr. Gleditsch, Dr. Robert McLeman of the University of Ottawa's Department of Geography presented the migration impacts of climate change. Dr. McLeman began with an overview of climate change-caused migration. He noted that the media has already identified the first climate change refugees, including those from Shishmaref, Alaska; the Cataret Islands, and the Lake Chad region.

Dr. McLeman provided a range of estimates for the number of future environmental refugees, ranging from 50 million refugees by 2100 to 1 billion refugees by 2050. He noted that predictions are based on identifying areas and populations exposed to negative climate change impacts. However, he noted that exposure does not equate to migration, climate-migration does not result from a simple stimulus-response, and there are numerous intervening socio-economic, cultural, and institutional factors. All of these caveats affect the accuracy of the estimates.

Dr. McLeman explained that migration may be caused by sudden onset events (e.g., hurricanes), persistent conditions (e.g., drought), or other stimuli. He noted that one of the earliest groups of climate change migrants will be oil workers migrating to the arctic. Dr. McLeman explained that climate change will generate migration stimuli nearly everywhere people live, including the arctic, high latitudes, wet tropics, mid- to low-latitudes, dry tropics, coastal plains, deltas, and small islands.

Dr. McLeman explained that climate events and conditions do not always stimulate migration and that multiple migration outcomes can be generated by a single climate event (e.g., brief evacuation, extended leave, permanent migration, new arrivals). He presented data from Hurricanes Katrina and Mitch that inform ensuing migration patterns. He noted one study that shows a 10% decrease in agricultural production in Mexico due to drought is associated with a 2% rise in Mexican-U.S. migration. Dr. McLeman explained that migration is one of a range of potential adaptive responses to environmental stress. Migration is used in many parts of world, is typically initiated by households, is not available to everyone, is not always used, and, in the worst case, could be the only adaptation option.

Dr. McLeman explained that vulnerability is a function of exposure, sensitivity, and adaptive capacity. He noted that migration changes the composition of the population left behind, which in turn changes the area's adaptive capacity. He further noted that migration is motivated by numerous non-climate factors (e.g., opportunity-seeking, cultural norms, lifestyle, love, persecution), with which climate interacts. He explained that most observed climate-related migration is not conflict-related, is internal or intra-regional, and generally follows established routes or transnational communities when international.

Dr. McLeman described numerous climate-migration models, including examples of each. Models include: historical climate-migration models, spatial vulnerability models, multi-level hazard analysis models, multi-stage regression models, and agent-based models. As part of one of the examples, he explained that migrants tend to be young, healthy, skilled, educated members of the middle class with uncertain land tenure and family ties elsewhere. Meanwhile, those less likely to migrate include wealthier classes, landowners, owners of fixed assets, those with strong local social networks, the poor and destitute, the elderly, the infirm, or those with broken families.

Dr. McLeman concluded with a list of challenges and opportunities. He noted many challenges related to a lack of data availability and reliability, including the lack of a single global database, fragmented data, and data missing reasons for migration. He noted other challenges including understanding system linkages and the role of intervening variables, as well as uncertainty about future climatic stimuli. Dr. McLeman listed three opportunities: to develop monitoring and data collection protocols, to enhance empirical research into environment and migration linkages, and to develop and improve migration models as climate change models improve.

Discussion: Socio-economic and Geopolitical Impacts

During the question and answer session, one participant highlighted the work of Robert Bates, which uses a different approach than described by Dr. Gleditsch to examine conflict. Dr. Gleditsch commented that he thought adding climate variables to Dr. Bates work would produce similar results to those he discussed.

Another participant asked whether climate change detection and attribution would affect the result that people unite in the face of natural disasters. He asked whether the existence of human cause or blame would affect the potential for conflict. Dr. Gleditsch clarified that the observation that people unite in the face of adversity does not only apply to natural disasters, but includes human-induced disasters such as bombings. He suggested that results may be different if a population's own government was responsible for the climate change. Dr. McLeman added that climate change adaptation planning was actually a fairly effective way to get otherwise quarreling parties to collaborate.

Dr. Gleditsch agreed with a third participant that climate conflict models should be focused on multiple stressors rather than climate as a solitary force. He noted that there has been some work in this area and reemphasized the notion of analyzing whether it is easier to address the issue by changing the climate variable or the other variables.

In response to another participant, Dr. McLeman acknowledged that he overlooked the effects of climate change on amenity migrants during his presentation. He agreed that climate change would affect the places to which affluent and retired people migrate.

A final participant asked whether the literature has examined the interaction between climate change, energy markets, and conflict and migration. Dr. Gleditsch reiterated the importance of resource scarcity in climate change. He suggested that there could be a benefit from a reduction in oil dependence and oil prices. Dr. McLeman noted that there may be an effect on energy markets from predicted rural-to-urban migration. He explained that rural residents tend to have a smaller energy footprint than urban residents, so that increased urbanization will lead to increased energy demand.

Panel Discussion: Incorporating Research on Climate Change Impacts into Integrated Assessment Modeling

Following the impact-specific sessions, a five-member panel discussed the incorporation of research on climate change impacts into integrated assessment modeling. The panel discussion was moderated by Dr. Elizabeth Kopits of EPA and included Dr. David Anthoff, University of California, Berkeley; Dr. Tony Janetos, Joint Global Change Research Institute, Pacific Northwest National Laboratory (PNNL); Dr. Robert Mendelsohn, Yale University; Dr. Cynthia Rosenzweig, NASA Goddard Institute for Space Studies; and Dr. Gary Yohe, Wesleyan University. The panel discussion started with comments from each of the panelist members and concluded with questions from the audience. Dr. Kopits framed the discussion by asking the panelists whether there was any hope in improving IAMs or whether it was only possible to outline a long-term research agenda.

David Anthoff, University of California, Berkeley

Dr. David Anthoff of the University of California at Berkeley, who works on the FUND model with Richard Tol, commenced the discussion. Dr. Anthoff reflected on each of the nine impact categories as presented by the workshop speakers and reflected on how well the state of the literature is incorporated into IAMs (specifically FUND). He noted that his comments would merely reflect how well the literature is reflected in FUND, without assessing the state of the primary research itself. He further qualified his comments by noting that they simply reflect his impressions from listening to the two days of presentations.

Dr. Anthoff suggested that FUND does a decent job incorporating the research for storms, water, sea level rise, forestry, and energy demand. He noted that Dr. Cropper's suggestion regarding the income elasticity for health impacts could be investigated fairly simply in the short-term. He suggested that the primary literature for agriculture seemed contradictory and does not provide the aggregated numbers necessary for IAM incorporation. He noted the difficulties associated with translating research on individual crops into the models. Dr. Anthoff noted that ocean acidification is not incorporated in any of the three models. He suggested that progress could be made to incorporate ocean acidification in the mid-term. Dr. Anthoff noted that FUND incorporates biodiversity loss, but that the primary research is rough. He noted that while energy demand is incorporated in IAMs, energy supply is not. He suggested the possibility of incorporating conflict is very far off. He noted that FUND incorporates a very simple migration model for sea level rise, but that other causes of migration are not incorporated.

Dr. Anthoff then suggested that primary researchers need to evaluate the IAMs to assess how well the data sources, damage functions, and outputs reflect the primary literature for each of the impact categories. He noted that uncertainty and extreme impacts are critical in IAMs, but were not discussed much during the workshop sessions. Lastly, Dr. Anthoff remarked that IAMs are severely understaffed and underfunded, particularly as compared to GCMs.

Tony Janetos, Joint Global Change Research Institute, Pacific Northwest National Laboratory

Next, Dr. Anthony C. Janetos of the Joint Global Change Research Institute suggested that there are many possibilities for improving IAMs based on the workshop presentations, noting that the physical impacts research seems to have advanced more than the valuation research. However, he suggested that very few of the advancements are readily incorporated into IAMs. He noted a need for additional understanding of thresholds, non-linear behavior, and process-level understanding. He further indicated a need to model interactions between sectors with an explicit representation of the sectors themselves, as well as the economic and physical factors (e.g. competition for water and land) that connect them.

Dr. Janetos identified several reasons that limit the generation of good central estimates of physical and economic parameters, which he noted are necessary for SCC development. First he cited the non-linearity and thresholds that pervade physical systems. He noted that some thresholds are not necessarily attributable to anthropogenic changes (e.g., climate changes driving pine beetle infestations). Dr. Janetos suggested a need to improve knowledge of the reference case, noting that the major drivers of big changes over the past half-century are human-driven (e.g., land-cover changes).

Dr. Janetos emphasized the importance of interactions among sectors, which he emphasized is a first-order problem. He explained that competition for water among various human uses and ecosystem uses is just the tip of the iceberg and not particularly well understood. He noted that aggregation and disaggregation issues are extremely important, which is a challenge for the response-surface approach.

Dr. Janetos then enumerated well-known deficiencies in the ecological models. For example, in the Vegetation/Ecosystem Modeling and Analysis Program (VEMAP), when all major ecosystem models were driven by same factors, they diverged. He noted that there has not been a subsequent reconciliation of that divergence. Dr. Janetos noted other deficiencies: ecological models typical do not include threshold responses; they underplay or omit biotic interactions like pests and pathogens; and DGVMs are largely unverified and potentially unverifiable.

Dr. Janetos suggested that it is useful and important, while difficult, to infer or develop statistically- or model-based response functions for use in reduced form IAMs. He noted that current damage functions are not robust beyond the ranges for which they were originally designed, and suggested that a process-based approach might be useful. He emphasized that uncertainty and error bars must be well characterized, noting that IAMs are better at doing this than the impacts community.

Robert Mendelsohn, Yale University

Dr. Robert Mendelsohn of Yale University shared brief remarks following Dr. Janetos. He noted that IAMs are not able to capture the level of detail available from climate modeling, ecological impact assessment, and damage assessment. He suggested some concern regarding the lack of connection between detailed impact studies and IAMs, however, he noted this lack of connection does not necessarily mean the IAMs are biased.

Dr. Mendelsohn emphasized the absolute necessity for studies to include adaptation. He highlighted that IAMs are interested in the actual damages of climate change, not the potential damages. He explained that significant adaptation will be implemented and models must acknowledge it. Next, Dr. Mendelsohn noted that the workshop seemed to be missing any discussion of catastrophic events and tipping points.

Next, Dr. Mendelsohn emphasized that the community should not be disheartened about IAMs or damage estimates. He emphasized that IAMs do a good job, in general, and that a lot of progress has been made over the last 20 years. He noted that natural science, ecosystem models, and economic models are all improving steadily, especially for short-term predictions. He acknowledged that long-term predictions are more difficult. He suggested a need for a third generation IAM to address spatial detail.

Finally, Dr. Mendelsohn suggested that the near-term agenda should be focused on capturing damage assessment work within impact models, so that IAMs can incorporate all current knowledge.

Cynthia Rosenzweig, National Aeronautics and Space Administration

Next, Dr. Cynthia Rosenzweig of NASA discussed three points and proposed a way forward.

First, Dr. Rosenzweig discussed the impacts, adaptation, and vulnerability (IAV) component of impacts assessment and valuation. She noted that adaptation has been severely underfunded but has been getting increased attention recently. She acknowledged a need to improve the biological, physical, and social science of impacts, as impacts research is much less advanced than climate science and has real effects on society. She highlighted an eagerness to work with and improve IAMs, but noted the great difficulty in doing so.

Second, Dr. Rosenzweig discussed the economic components of impacts assessment and valuation. She suggested that current work (e.g., SCC) is focused on justifying mitigation action. She suggested the need for an adaptation lens in economics work, and even analysis of the balance of resource allocation between adaptation and mitigation. She questioned whether IAMs are capable of addressing all three questions. She suggested a need to understand the economic underpinnings of adaptation, to better understand state changes arising from incremental and marginal changes, and to better address equity and environmental justice issues.

Third, Dr. Rosenzweig discussed integration of scales, of mitigation and adaptation, and of sectors. She noted that urban areas are where all sectors are integrated. She suggested climate change assessment in cities be conducted.

Finally, Dr. Rosenzweig suggested a need for on-going trans-disciplinary groups to work to improve basic research and translation. She highlighted EMF-24, OCMIP, and VEMAP as examples of trans-disciplinary efforts aimed at creating processes and structures for progress. She suggested collaboration with the National Climate Assessment and with international impacts efforts. She highlighted a movement to coordinate IAV scientists behind research questions. She noted the United Nations Environment Programme (UNEP) Programme of Research on Climate Change Vulnerability, Impacts and Adaptation (PRO-VIA), a new organization aimed at setting research questions and directions.

Gary Yohe, Wesleyan University

Finally, Dr. Gary Yohe of Wesleyan University shared his comments. He noted that his comments serve as an outline of the more complete paper he wrote to address the charge questions.

First, Dr. Yohe suggested a need for humility regarding our confidence estimates of the research. He emphasized a need to identify uncertainty issues.

Second, Dr. Yohe suggested a possible Type 3 Error in assessing economic impacts from climate change to build the SCC, cautioning scientists and economists not to spend time addressing the wrong issues, with little value added. He discussed his use of PAGE with Chris Hope to do a Monte Carlo analysis of probabilities with a range of different parameter assumptions. The analysis concluded that, in PAGE, differences in damage estimates were not as important as other variables such as time preference, risk aversion, etc.

Third, Dr. Yohe instead suggested an alternative approach for estimating benefits of marginal reductions in emissions, with higher value added. He suggested that an iterative process be built to set a target and work towards a shadow price. First, he suggested using an assessment of climate risk to determine the long-term objective and medium-term climate budget. Second, he suggested the U.S. contribution to this budget could be determined, working within the political process. Third, the results from this analysis could be used to price carbon for non-climate policy needs. Within this process, IAMs would be used to check the reasonableness of the assessment, to design cost-minimizing approaches (including net economic damages), and to highlight areas where adaptation in economic sectors will be most productive.

Panel Discussion

Following remarks from the five panelists, the panel discussed questions from the audience. One participant asked what detail is needed, what uncertainty is important to characterize, and what factors most influence the results in IAMs. She noted the orders of magnitude difference resulting from carefully conducted impact analyses. Dr. Janetos agreed that modelers must identify which complexity is important to include. He noted structures arising to address this question, including validation studies and a process-level understanding of the individual sectors. Dr. Anthoff noted that exploring relative importance is a key strength of IAMs. He noted that IAMs can use ranges and limits from the impact community as inputs, to determine how much the SCC reacts to a full range of inputs from a single sector.

Another participant questioned the interaction of high non-use and non-market values with the imposed limit that damages cannot be more than GDP. A third participant underscored a couple of Dr. Anthoff's comments. He emphasized the importance of the tails of impacts (as opposed to means, medians) to policy makers. He highlighted the need for impact studies beyond 2100. He emphasized the small size of the IA community. He noted that a lot of the community's time is spent on discussing their work at meetings like this workshop, which limits time available to do the work. Dr. Rosenzweig expressed her hope that by expanding the community that is working on rigorously comparing models, they will be able to work with and help integrated assessment modelers by providing more rigorous estimates.

Closing Remarks

The workshop concluded with closing remarks from Dr. Rick Duke, Deputy Assistant Secretary for Climate Policy at DOE and Dr. Al McGartland, Director of the National Center for Environmental Economics at EPA.

Summary Comments by U.S. Department of Energy

First, Dr. Rick Duke, the DOE Deputy Assistant Secretary for Climate Policy, thanked the participants for attending, particularly those that braved the weather on Day 1. He expressed his appreciation of the great conversation between natural scientists and economists, noting that he was struck by Dr. Anthoff's desire to engage natural scientists to review economists' work on impacts.

Dr. Duke again noted that the workshop grew out of the interagency SCC work, which has since been used in rulemaking. He acknowledged that the SCC values have numerous limitations that need to be addressed, some beyond the scope of these workshops. He outlined a challenge to the community on two timescales: to help to make better regulatory decisions in the near-term and to promote research to improve assessment and valuation in the long-term.

Dr. Duke highlighted the need to evaluate the impacts of higher temperature outcomes, as well as median outcomes. He noted that climate policy is much like insurance policy -- a primary goal is to reduce the consequences of particularly unfavorable states of the world (e.g., high climate sensitivities) as well as to reduce expected losses. He emphasized the importance of evaluating the more significant outcomes given the major challenges in achieving planned mitigation.

He closed by thanking the presenters, the broader research community, and DOE's partner, EPA.

Summary Comments by U.S. Environmental Protection Agency

Finally, Dr. Al McGartland, Office Director for EPA's NCEE, extended both personal and EPA thanks to the participants for attending despite the inclement weather. He said that he intended to finish the conference with a ray of hope.

First, he noted that due to the field's interdisciplinary nature, everyone in the community must stretch to accommodate other groups. He emphasized that policy institutions have to stretch as well. Dr. McGartland noted that the SCC process was aimed at developing a set of numbers and asked if the right questions are being asked. He noted that the process is not aimed at legislation or the next Kyoto Protocol. Rather, the process seeks a shadow price so that EPA and DOE can incorporate the benefits of carbon reduction in any rule affecting carbon emissions.

Next, Dr. McGartland highlighted the significant progress that has been made in risk assessment since the work on particulate matter, lead, and pesticides in the 1980s. He suggested that simply duplicating the historic rate of progress in this area would be great. He noted that EPA's long-term strategy is dominated by regulatory work in areas where there are large net benefits.

Looking forward, Dr. McGartland highlighted a number of good points from the workshop. He emphasized the need to address interactions among sectors. Finally, he highlighted his commitment to move forward with the SCC using a transparent process.

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis

Sponsored by United States Environmental Protection Agency (EPA), U.S. Department of Energy

January 27-28, 2011 — Capital Hilton, Washington, DC

Workshop Agenda
Federal Meeting Room

RESEARCH ON CLIMATE CHANGE IMPACTS AND ASSOCIATED ECONOMIC DAMAGES

DAY 1

Workshop Introduction

8:55 – 9:00 ***Welcome***
Elizabeth Kopits, U.S. Environmental Protection Agency

9:00 – 9:20 ***Opening Remarks – Progress in estimating climate change impacts***
Michael Oppenheimer, Princeton University

9:20 – 9:40 ***Opening Remarks – Progress in valuing climate damages***
William Cline, Peterson Institute for International Economics

9:40 – 9:45 ***Questions***

Sessions covering research on various impact categories:

Storms and Other Extreme Weather Events
Moderator: Alex Marten, U.S. Environmental Protection Agency

9:45 – 10:05 ***Impact of Climate Change on Storms and Other Extreme Weather Events***
Tom Knutson, National Oceanic and Atmospheric Administration

10:10 – 10:30 ***Global Damages from Storms and Other Extreme Weather Events***
Robert Mendelsohn, Yale University

10:35 – 10:55 **Open Facilitated Discussion**

10:55 – 11:05 ***Break***

Water Resources

Moderator: Robert Kopp, U.S. Department of Energy

11:05 – 11:25	***Hydrological/Water Resource Impacts of Climate Change*** Ken Strzepek, University of Colorado, Boulder, and Massachusetts Institute of Technology
11:25 – 11:45	***Estimating the Economic Impact of Changes in Water Availability*** Brian Hurd, New Mexico State University
11:45 – 12:10	**Open Facilitated Discussion**

12:10 – 1:00 ***Lunch***

Agriculture

Moderator: Charles Griffiths, U.S. Environmental Protection Agency

1:00 – 1:20	***Biophysical Responses of Agro-ecosystems to Climate Change*** Cynthia Rosenzweig, NASA Goddard Institute for Space Studies
1:20 – 1:40	***Estimating the Economic Impact of Climate Change in the Agricultural Sector*** Wolfram Schlenker, Columbia University
1:40 – 2:20	**Open Facilitated Discussion**

Human Health

Moderator: Charles Griffiths, U.S. Environmental Protection Agency

2:20 – 2:40	***Climate-Associated Changes in Health Conditions/Diseases and Air Pollution*** Kristie Ebi, Carnegie Institution for Science
2:40 – 3:00	***Estimating the Economic Value of Health Impacts of Climate Change*** Maureen Cropper, Resources for the Future and University of Maryland, College Park
3:00 – 3:40	**Open Facilitated Discussion**
3:40 – 3:50	***Break***

Sea Level Rise

Moderator: Robert Kopp, U.S. Department of Energy

3:50 – 4:10	***Sea Level Impacts of Climate Change*** Robert Nicholls, University of Southampton
4:10 – 4:30	***Estimating the Economic Impact of Sea Level Rise*** Robert Tol, Economic and Social Research Institute
4:30 – 5:10	**Open Facilitated Discussion**

- **DAY 2**

Day 2 Introduction

8:30–8:40 ***Welcome; Recap of Day 1; Overview of Day 2***
Elizabeth Kopits, U.S. Environmental Protection Agency

Impacts Sessions Continued:

Marine Ecosystems and Resources

Moderator: Chris Moore, U.S. Environmental Protection Agency

8:40 – 9:00 ***Modeling Climate and Ocean Acidification Impacts on Ocean Biogeochemistry***
Sarah Cooley, Woods Hole Oceanographic Institute

9:00 – 9:20 ***Modeling Climate and Acidification Impacts on Fisheries and Aquaculture***
Paul McElhany, National Oceanic and Atmospheric Administration

9:20 – 9:40 ***Economic Impact of Climate Change and Ocean Acidification on Fisheries***
David Finnoff, University of Wyoming

9:40 – 10:00 ***Non-market Valuation of Climate and Acidification Impacts on Marine Resources***
John Whitehead, Appalachian State University

10:00 – 10:10 *Break*

10:10 – 10:50 **Open Facilitated Discussion**

Terrestrial Ecosystems and Forestry

Moderator: Steve Newbold, U.S. Environmental Protection Agency

10:50 – 11:10 ***Biological Responses of Terrestrial Ecosystems to Climate Change***
Karen Carney, Stratus Consulting

11:10 – 11:30 ***Estimating the Economic Impact of Climate Change on Forestry***
Brent Sohngen, Ohio State University

11:30 – 11:50 ***Valuing Climate-associated Changes in Terrestrial Ecosystems and Ecosystem Services***
Alan Krupnick, Resources for the Future

11:50 – 12:30 **Open Facilitated Discussion**

12:30 – 1:30 ***Lunch***

Energy Production and Consumption
Moderator: Stephanie Waldhoff, U.S. Environmental Protection Agency

1:30 – 1:50 ***U.S. Energy Production and Consumption Impacts of Climate Change***
Howard Gruenspecht, U.S. Energy Information Administration

1:50 – 2:10 ***Impacts of Climate Change on Global Energy Production and Consumption***
Jayant Sathaye, Lawrence Berkeley National Laboratory

2:10 – 2:50 **Open Facilitated Discussion**

Socio-economic and Geopolitical Impacts
Moderator: Alex Marten, U.S. Environmental Protection Agency

2:50 – 3:10 ***Regional Conflict and Climate Change***
Nils Petter Gleditsch, Peace Research Institute Oslo

3:10 – 3:30 ***Migration Impacts of Climate Change***
Robert McLeman, University of Ottawa

3:30 – 3:40 ***Break***

3:40 – 4:20 **Open Facilitated Discussion**

Panel Discussion: Incorporating Research on Climate Change Impacts into Integrated Assessment Modeling

4:20–5:20 Moderator: Elizabeth Kopits, U.S. Environmental Protection Agency

Panelists:

- David Anthoff, University of California, Berkeley
- Anthony Janetos, Joint Global Change Research Institute, Pacific Northwest National Laboratory
- Robert Mendelsohn, Yale University

- Cynthia Rosenzweig, NASA Goddard Institute for Space Studies
- Gary Yohe, Wesleyan University

Closing Remarks

5:20–5:25 ***Summary Comments by U.S. Department of Energy***
Rick Duke, Deputy Assistant Secretary for Climate Policy

5:25–5:30 ***Summary Comments by U.S. Environmental Protection Agency***
Al McGartland, Director of the National Center for Environmental Economics

Progress in Estimating Climate Change Impacts

Michael Oppenheimer
Program in Science, Technology, and Environmental Policy
Princeton University

ABSTRACT

The assessment of potential impacts of climate change has progressed over time from taxonomies and enumeration of the magnitude of potential direct effects of climate change on individuals, societies, species, and ecosystems according to a limited number of metrics toward a more integrated approach that encompasses the vast range of human response to risk, perceived risk, and experience. Recent advances are both conceptual and methodological, and focus on analysis of some consequences of climate change that were viewed heretofore as intractable. This presentation will review a selection of these developments and represent them through a handful of illustrative cases. A key characteristic of the emerging areas of interest is a focus on understanding human responses to impacts and developing integrated approaches which assess impacts in an evolving socioeconomic and policy context.

1. Dynamic vulnerability

While climate impact analysis in some sectors, notably agriculture, has attempted to integrate human responses by accounting in part for the potential to adapt, such approaches have been marginal and particular, and unable to estimate the full interaction among humans, socioeconomic systems, and the climate. Ideally, impacts would be assessed in the context of development scenarios which capture vulnerability as an evolving feature rather than a static set of capacities and limits. Responses would also be dynamic, described as resulting from experienced-based perception of risk as well as "objective" risk. The latter is particularly important in situations where impacts are dominated by extreme and/or rare events, where uncertainty is large, and where learning is a critical determinant of response.

The SRES[1] represented a potential step in this direction. However, they were mainly used in impact analysis to determine a range of climate futures rather than the range of human responses. The emerging Shared Socioeconomic Pathways[2] may provide an improved basis for integrated analysis of impacts.

2. Mapping human responses and evaluating their indirect consequences

To date, impact studies have naturally tended to focus on the direct effect of changes in the physical climate system (including sea level). But some of the key impacts are indirect, arising from decisions stimulated by the initial physical changes, or expectation thereof. For example, it is well known that people migrate, sometimes temporarily, sometimes permanently, in response to unfavorable environmental changes, including climate.[3] These movements have the potential for large scale effects on natural resources, ecosystems services, and species. They are second order in the sense of being indirect but not necessarily in the sense of their magnitude[4].

For example, one recent study suggests that a potential relative shift in agricultural productivity in western South Africa compared to the eastern part of that country could encourage cultivation in regions now designated for protection for species conservation purposes[5]. Such indirect impacts may in some cases be larger than the direct consequences of the changing climate for the species at risk. While ability to reliably quantify such responses runs into the limits imposed by regional modeling and downscaling, the same is true of the direct responses. On the other hand, modeling of some responses, like human migration[6] and the potential for large associated indirect impacts, is in its infancy, and this presents a key obstacle. But at the present time, it is at least possible to investigate which areas may become vulnerable because their relative attractiveness for cultivation or other economic activities is projected to increase. Other shifts in human settlement such as those driven by sea level rise could likewise bring about large scale indirect impacts.

Such impacts might fall under the category of action-at-a-distance, in the sense that a climate change in one region stimulates responses which have impacts on people and resources in another region(s). The potential number of such reverberations is large, including, for example via the interlinked global market system (discussed further in section 3, below).

3. Integration of impacts, adaptation, and mitigation (biofuels, geo-engineering)

It has long been known that adaptation actions bear consequences for mitigation strategies, e.g., projected increases in cooling and decreases in heating requirements bear implications for strategies to mitigated carbon dioxide emissions. A new focus is developing on the implications which mitigation actions bear for impacts and adaptation. For example, there is evidence that the conversation of unmanaged forest and cultivated land for the purposes of growing crops intended for bio-fuel feed stocks (encouraged in some instances by energy- and climate-related policy initiatives) could bring along substantial consequences for biodiversity and world grain prices, respectively[7]. A complex set of subsequent human responses would also result from the latter. These in turn would affect the initial mitigation actions by raising their cost and potentially undercutting political support for them.

A second emerging area of interest is geo-engineering, particularly short-wave radiation management, which is projected to produce significant, potentially harmful climate impacts far removed for the location of initiation of the mitigation actions[8]. Such impacts would not only result in various human impacts (via the water and agricultural sectors) and responses, but have the potential to feed back through the political system and affect judgments about the viability of this mitigation approach. Both of these examples illustrate the tightly couple nature of the mitigation-impact-adaptation system and the unavoidable necessity of understanding both political and economic consequences to adequately project future outcomes.

4. Interacting systems and stressors

Consideration of interacting stressors and systems[8] are not new to climate impact studies but just as with the topics above, a new emphasis is emerging which examines such interactions through the lens of human responses to general socioeconomic conditions as well as climate-related circumstances. Impacts of climate change evolve in the context of multiple additional environmental stressors including air pollution, water pollution, and the massive consequences resulting from urbanization and other concentrations of human population such as occur in deltaic and estuarine regions. In urban agglomerations, we see the potential increase in efficiency of use of some resources (energy), accompanied by the shifting of environmental natural resource exploitation to outlying regions (water withdrawal, food production). Interacting stresses include 1) the squeezing of an increasing population within a potentially shrinking land area (due to sea level rise), 2) the increasing health risk of a growing population subject to an increasing urban heat island effect, and 3) the increasing problems associated with water and solid waste disposal under conditions of increased heat and population density.

5. Extremes and disasters

Consideration of extremes and disasters provides an additional framework for understanding potential impacts, adaptation, and socioeconomic ripple effects. Much of the past climate change impacts research has focused on outcomes of changes in mean values of climate parameters. The difficulties entailed in attempting to account for changes in extremes include among others, the difficulty of projecting changes in many extremes, and the social and geographic specificity of conditions of vulnerability and exposure which combine with extreme physical events to produce extreme impacts and disasters.

The upcoming IPCC Special Report, Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), is expected to provide new insights which should help define an emerging research agenda on such impacts. One noteworthy feature is the importance of the timing of events and their interactions, which can amplify the effects of both underlying trends in the mean climate as well as the effects of individual extreme events.

6. Methodological advances

As series of developments are gradually improving the ability to understand causation, to project future impacts and responses, and to permit a fuller risk management approach to impact assessment. Among these are advances in detection and attribution, further exploitation of methods commonly used in econometrics[9,10] , and probabilistic and multi-metric frameworks for evaluating risk.

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Progress in Estimating Climate Change Impacts

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At

Climate Damages Workshop

USEPA/DoE

27 January 2011

Overview

- Systematic assessment of potential impacts of climate change and valuation of damages goes back to 1970s*
- Recent advances in process-based and statistical modeling
- Limited progress is accounting for adaptation capacity and human responses in general
- Emerging issue: need an integrated approach to impact/adaptation/development

*for example, Williams, J. (ed.): 1978, *Proceedings of an IIASA Workshop on Carbon Dioxide, Climate, and Society*, Pergamon Press, Oxford, February 21–24

Progress in physical exposure and impact modeling

- GCM resolution improves, downscaling, RCMs (e.g., watershed-scale, coral reef studies)
- Statistical modeling of responses (to variability): agriculture, migration, conflict
- Deployment of GIS data (coastal impacts)

Where progress has been slow

- Incorporating adaptation capacity into impact modeling (arises in social and natural systems): obscure

- Understanding the gap between capacity and implementation of adaptation

- Assessing indirect effects

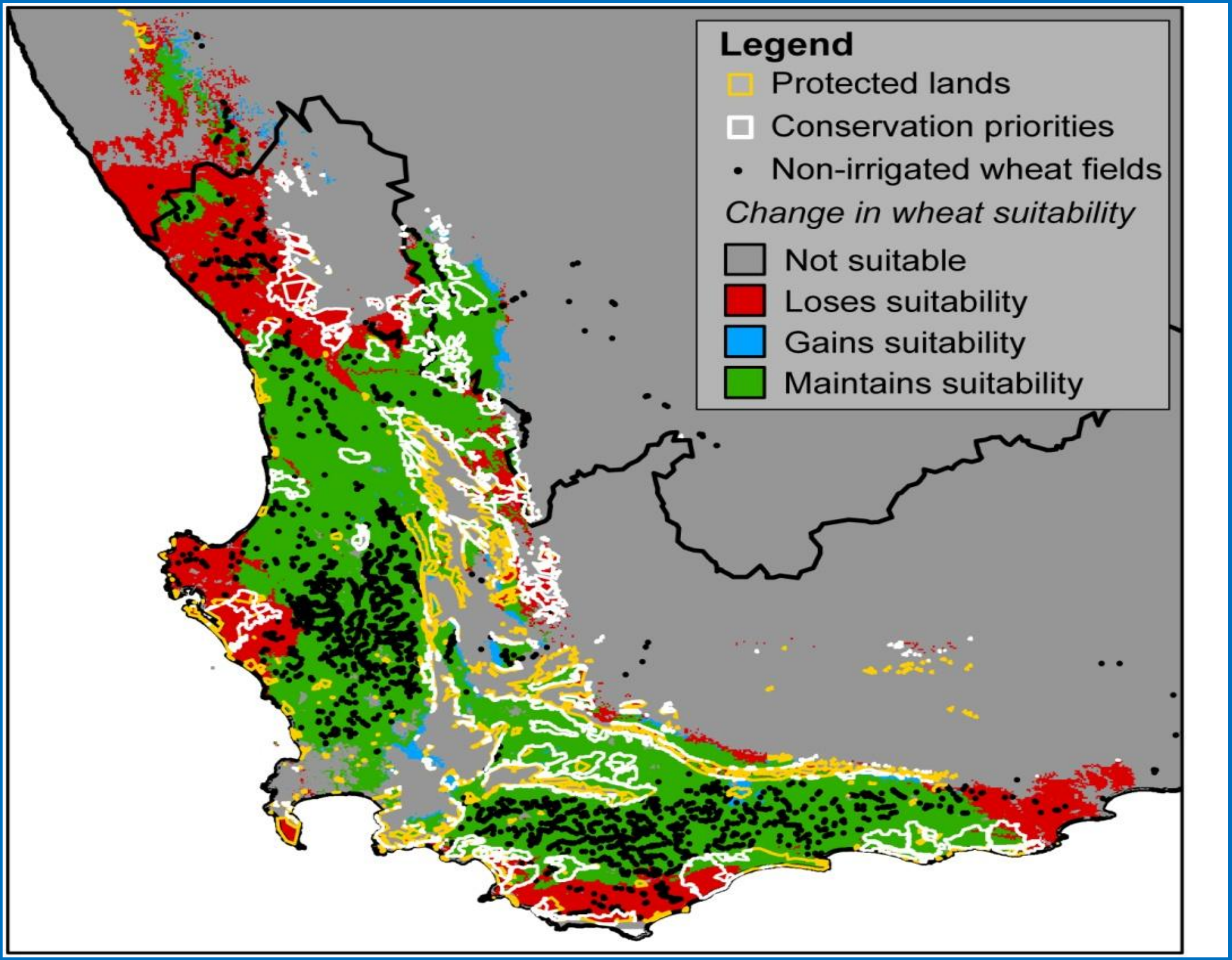
- Developing a comprehensive approach: development paths plus top-down/bottom-up

Emerging areas

Human Responses to Climate Change and their Indirect and Remote Consequences

>>>Migration of human population affects resources and people at a distance (Leman abstract)

>>>Shift in regions exploited for agriculture threatens or benefits unique ecosystems/species



Overlap of areas losing crop suitability and conservation land in Cape region, year 2050

Turner et al, Cons. Letters

Integration of Impacts, Adaptation with Mitigation

>>>Bio-fuel feedstock production impacts on land use for biodiversity, food production and prices (Schlenker abstract) and various reverberations, including political

>>>Impacts of geo-engineering

Interacting Systems and Stressors

>>>Urbanization with urban heat islands and climate change (McCarthy et al 2010): affects energy and resource use and human health

>>>Upstream water diversion causing deltaic subsidence with exposure to sea level rise (Ericson et al)

Deltas and Upstream Reservoirs Worldwide

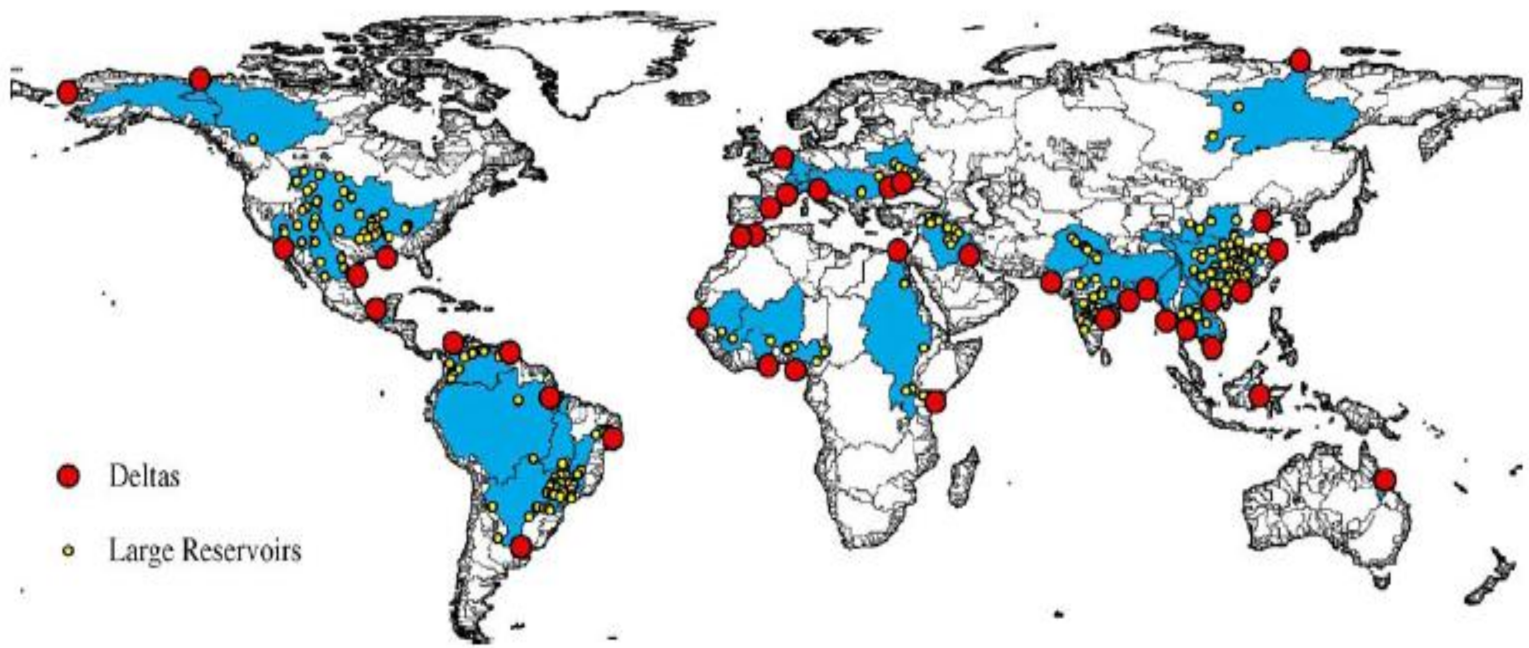


Fig. 1. Global distribution of the 40 deltas analyzed in this study, the potentially contributing drainage basin area of each delta (blue) and the large reservoirs (>0.5 km^3 maximum capacity) in each basin.

Ericson et al, Global and Planetary Change 50 (2006) 63–82

Climate Extremes and Disasters

>>> Local specificity of exposure and vulnerability (Knutson abstract)

>>> How might learning occur as history becomes a poor guide to the future (SREX: lessons from disaster response)?

Dynamic Vulnerability

>>> Impacts depend on vulnerability, which evolves with development (e.g., affordability of coastal defense)

>>> Both increases and decreases occur to vulnerability as learning competes with mal-adaptation and risk-shifting behavior (withdrawal vs. hardening in some cases of flood-plain defense)

>>> How to integrate the contextual aspect associated with diverse potential development pathways into

Not just a developing country issue… welcome to Atlantic City

Courtesy Norm Psuty

Valuation of Damages from Climate Change[1]

William R. Cline
Peterson Institute for International Economics
January, 2011

Introduction

It is an honor to be invited to speak at this workshop. I look forward to hearing the latest views of the prominent experts assembled by the organizers. I believe the EPA and other agencies made a good start on estimating the social cost of carbon in the February 2010 report of the Interagency Working Group (2010). Strengthening those estimates has become all the more important with the delay of US climate legislation and the de facto recourse at present to Plan B, in which EPA enforcement and action by the three Regional Climate Initiatives at the state level constitute the interim delivery mechanism for internationally promised US action. I will stress the importance of strengthening the damage estimates in two dimensions: treatment of catastrophic damage and choice of the central discount rate.

Brief Retrospective[2]

Let me first provide a brief retrospective on cost-benefit analysis of climate change. My 1992 book (Cline, 1992) used estimates by the EPA and other sources to estimate that 2.5°C warming from a doubling of carbon dioxide by late this century would impose damages of 1 percent of GDP on the US economy. In order of importance, the damages were in agriculture, electricity requirements for increased cooling in excess of reduced heating; water supply; sea-level rise; loss of human life; tropospheric ozone pollution; species loss, and forest loss. I note that these are broadly the same categories on the agenda of this conference. However, I emphasized that the analysis should cover 300

[1] Remarks at the conference on Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis, Environmental Protection Agency and US Department of Energy, Washington DC, January 27-28, 2011.

[2] For a recent overview, see Cline (2010a).

years, the horizon before major re-absorption into the deep ocean. Using the scientific relationships reported in the first IPCC review, I estimated that over that horizon warming could reach 10°C, increasing damage to 6 percent of GDP in the central case and three times as high in a higher-damage variant. I invoked the Ramsey (1928) discounting method that imposes zero pure time preference, or discounting for impatience, for intergenerational comparisons. With my discount rate of 1.5 percent for per capita income rising at 1 percent, I estimated that -- with modest risk-weighting, a cut in greenhouse gas emissions by one-half at an annual abatement cost of around 3 percent of GDP was warranted on social cost-benefit grounds. Inclusion of catastrophic damages would have reinforced the conclusion. Using his DICE model and a considerably higher discount rate, William Nordhaus (1993) concluded that much less abatement was warranted. In the 1995 IPCC survey of economic modeling results, social cost of carbon by 2010-20 was placed in a range of about $5-$7 (1990 dollars) per ton of CO_2 in estimates by Nordhaus as well as some other modelers, but reached $18 (or $30 at 2010 prices) in my alternative runs of the DICE model using my discounting (Pearce et al, p. 215; Cline, 1997, pp. 110-17).

Even after an important revision of the DICE model in 2000 that tried to incorporate catastrophic damages based on surveys of expert opinion, by 2008 Nordhaus (2008) continued to estimate low optimal carbon dioxide taxes ($11 per ton in 2015 and still only $24 by 2050) and high optimal emissions paths (rising from 30 $GtCO_2$ now to 44 $GtCO_2$ in 2050) and high optimal atmospheric concentrations (480 ppm by 2050 and 660 ppm CO_2 by 2200). In sharp contrast, in his 2007 review for the UK Treasury, Nicholas Stern and his team found that social benefits of greatly exceeded abatement costs of limiting atmospheric concentrations to 500-550 ppm CO_2-equivalent, requiring emissions about one-third lower than the 2000 levels by 2050 and even lower thereafter (Stern, 2007). Stern used the PAGE model with a damage function quite similar to that used in Nordhaus' DICE model, and found that by 2200 global damages under business as usual would amount to 5-20 percent of world product. Using Ramsey's zero pure time preference and considering an infinite horizon thereafter, the Stern Review also placed the equivalent “now and forever” value of unrestrained damages at 5 to 20 percent of world GDP. He placed the abatement cost for the 500-550 ppm ceiling at -1% to +3.5% of world product by 2050, and the average cost at about $50 per ton of CO_2 in 2015, falling to about $30 by 2025. (p. 260) Essentially the same two central analytical features of my 1992 book, Ramsey-type discounting with zero pure time preference and the adoption of a long horizon, led Stern to the same conclusion that much more aggressive abatement was warranted on social cost-benefit grounds than identified by Nordhaus and some other modelers.

At this point Martin Weitzman (2007) entered the debate with a new emphasis on the implications of uncertainty about catastrophic effects. He judged that Stern was probably right for the wrong reason. The pure time preference rate should not be set at zero, but future catastrophes from climate change could be severe enough to drive consumption levels below those of the present and hence discounting for consumption would turn negative. The “fat tail” of the probability distributions of warming and damage are at the heart of this risk, and they introduce uncertainty about the discount rate that should be used. However, Weitzman’s mathematics involve a singularity in which the present value of future loss is infinite, so his analysis is difficult to make operational. Sterner and Persson (2007) also arrive at a favorable evaluation of Stern-like aggressive action but argue that this conclusion could be reached “even with Nordhaus’ conventional assumptions of a fairly high rate of discount … [if] the escalation of prices for scarce environmental services were taken into account.”

Catastrophe Update and Super-Contingent Valuation

Scientific work in recent years has increased the concern we should have about catastrophic effects of climate change. The three catastrophes usually considered are: collapse of the ocean conveyor belt that causes the Gulf Stream and keeps Northern Europe warm; melting of the Greenland ice sheet or collapse of the West Antarctic ice sheet, either of which would raise sea levels by 7 meters ;

and a runaway greenhouse effect as methane is released from clathrates on continental shelves and from permafrost. With respect to the conveyor belt, a 2005 study found that "the Atlantic meridional overturning circulation has slowed by about 30 percent between 1957 and 2004" (Bryden, Longworth and Cunningham, 2005). With respect to the Greenland ice sheet, in a 2005 study Meinshausen (2005) found that " the loss of the Greenland ice-sheet may be triggered by a local temperature increase of approximately 2.7°C, which could correspond to a global mean temperature increase of less than 2°C."

Perhaps the most disturbing new evidence on catastrophic risks concerns massive extinctions as a consequence of an eventual loss of oxygen in the oceans, a buildup in anaerobic bacteria, and the release of hydrogen sulfide from the oceans in amounts toxic for plants and animals. A 2005 study by Kump, Pavlov, and Arthur (2005) found that "fluxes of H_2S to the atmosphere … would likely have led to toxic levels …[that served] as a kill mechanism during the end-Permian, late Devonian, and Cenomanian-Turonian extinctions" (p. 397). In the first of these, the Permian-Triassic extinction event 251 million years ago, some 90 percent of species on land and in the oceans became extinct. Volcanic eruptions in the Siberian "traps" (lava-flows) are likely to have caused sharp increases in atmospheric concentrations of CO_2, methane releases from clathrates, and an increase in global temperatures by levels 6°C (Benton, 2003). "The evidence at hand links the mass extinctions with a changeover in the ocean from oxygenated to anoxic bottom waters" (Ward, 2010, p. 189). A shut-down in the ocean conveyor belt would have caused this changeover, setting the stage for the buildup of anaerobic bacteria and eventual release of hydrogen sulfide. Similarly, a 2007 study found that over the past 520 million years, extinctions were relatively high during warm "greenhouse" phases; four of the five worst mass extinctions were associated with such phases (Mayhew and Benton, 2007).

The time scale for such a phenomenon is unknown, but is probably on the order of thousands of years.[3] Eventually a world free of ice sheets would mean sea levels 60 to 80 meters higher than today.[4]

[3] Lee Kump, personal communication, November 1, 2007.

If the H_2S hypothesis is correct, humans could probably survive using gas masks out of doors and living in atmospheric-controlled chambers, or at least those who could afford to do so would. However, food supply would be challenging, because of the likely die-off of livestock animals.

These stakes pose an acute problem for cost-benefit analysis. Suppose the time horizon is 2,000 years. Suppose world product stabilizes at $500 trillion (compared to $340 trillion in the EMF-22 scenarios for 2100, and $50 trillion at present), and world population, at 9 billion. The Interagency report's lowest discount factor of 2.5 percent expands $1 over 2,000 years to $2.8 x 10^{21} dollars, or $2.8 billion trillion. The policy maker would have to conclude it is not worth spending even a single cent today to avoid the complete elimination of one year's worth of world product 2,000 years from now.

Hopefully, policy makers do not make calculations about such large but long-term stakes in this fashion. It may be helpful to resort to a sort of "super-contingent valuation" thought experiment. Instead of conducting a survey of how much the typical household would be willing to pay to save the polar bear, one could think of how policymakers seem to be expressing revealed contingent valuation of catastrophic damage. Consider the pledges at Copenhagen. The industrial countries have stated that they will provide $100 billion annually by 2020 to help developing countries curb greenhouse gas emissions. Business as usual emissions of developing countries are likely to be 21 $GtCO_2$ by then (Cline, 2010b). The pledges so far from Copenhagen amount to reducing that amount by only 0.7 $GtCO_2$, or by less than 4 percent. Suppose the policymakers believed that by pledging resources, they could induce the developing countries to more than double that effort, attaining a 10 percent reduction. That would amount to a cutback of 2.1 billion tons at $100 billion, implying an average abatement cost of $50 per ton of carbon dioxide. That is twice the central Interagency estimate for 2020. So why not think of the Copenhagen pledges as revealed contingent evaluation by industrial country leaders placing the value of

[4] The lower figure is from Hansen et al (2008) as interpreted in Cline (2010a); the higher figure, from Ward (2010, p. 39).

avoiding catastrophe at about equal to the value of the other global warming damages that have been counted in the models.

Discount Rate Once Again

Interestingly enough, this exercise yields a price that is much closer to the Interagency's low-discount case ($42) and lower than the 95th percentile high-damage case ($81). This comparison brings one right back to the two central issues that have challenged the economics of global warming from the start: the discount rate and proper valuation of catastrophic risk. I have just discussed one important catastrophic risk. Let me say three specific things about the discount rate.

First, returning to proper discounting for a time scale of one or two centuries rather than millennia, I would emphasize that the particular value chosen for one specific parameter makes an immense difference: the so-called elasticity of marginal utility, or the percent decline in marginal utility for a percent increase in per capita consumption. In the Ramsey equation, the discount rate equals pure time preference, which many would agree should be set at zero for intergenerational comparisons, plus the elasticity of marginal utility multiplied by the growth rate of per capita income. Stern's use of unity for the elasticity of marginal utility, or a logarithmic utility function, probably understates how rapidly marginal utility falls off as consumption rises. But the value of 2 used for this elasticity by both Nordhaus and Weitzman probably overstates it. The evidence I would cite is the structure of progressive tax regimes in industrial countries. A parameter of unity would lead to a strictly proportional tax, in which it is considered fair that the poor man pays the same percent of income as the rich man. We observe more progressive structures than that. But a parameter of 2 would mean, for example, that the average (not marginal) income tax on an income of $650,000 would be 79 percent if the tax on an income of $20,000 is 10 percent.[5] That is far more progressive than we observe. The value of 1.5 that I used in 1992 still seems about right to me; in this example it would generate an average tax rate of 42 percent for the rich household, much closer to what we observe.

Second, I urge the Interagency working group to use the long-term Treasury Inflation Protected (TIP) bond as the best measure of the pre-tax risk-free real rate for discounting consumption. Using instead the long-term nominal rate and deflating by actual inflation gives an understatement during the high-inflation 1970s and early 1980s, but an overstatement for the following decades because markets consistently lagged behind the actuality of falling inflation in adjusting inflation expectations. Using the available 20- and 30-year TIP rates since 2004, the real rate has averaged 2.1 percent (Federal Reserve, 2011). When the Interagency's translation to after-tax return at 73 percent of the pre-tax rate is applied, that yields 1.5 percent as the discount rate for consumption. So I would argue that the "descriptive" approach using the observed consumption discount rate should place it at 1.5 percent, more than a full percentage point below the rate of 2.7 percent used in the Interagency report for the same concept.

Third, per capita growth is the other component of the discount rate. The Interagency group expects global per capita income to rise at 2 percent annually through 2100. Actually the EMF-22 projection for 2100 amounts to an annual per capita growth of 1.77 percent for 2010-2100 (Interagency Working Group, 2010, table 2). Moreover, that is at market exchange rates. The growth rate will be lower at purchasing power parity, at about 0.8 times as much based on the Balassa-Samuelson relationship (Subramanian, 2011). The consumption discount rate would then be 1.5 for the elasticity of marginal utility, multiplied by 1.4 percent for ppp growth in per capita income, or 2.1 percent. That

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[5] In the constant relative risk aversion (CRRA) utility function, utility from consumption level C is: $U = C^{(1-\eta)}/(1-\eta)$, where η is the absolute value of the elasticity of marginal utility. For a given average tax rate for the poor family, the socially optimal average tax rate for the rich family is the level that just equates the reduction in utility for each of the two families as a consequence of the tax.

would only be for the 21st century. The 22nd century should be discounted at a lower rate because per capita growth would decelerate.

An insurance approach

Even with refinements in discounting, the ultimate difficulty of placing a value on catastrophic effects raises doubts about the use of integrated assessment models to arrive at optimal paths of abatement and carbon dioxide shadow prices. That is why both Stern and Weitzman adopt essentially an insurance approach to global warming policy, even though they disagree on the discount rate. Stern suggests a ceiling of 500-550 ppm for carbon-dioxide-equivalent concentrations. At Copenhagen in December 2009, heads of state set a ceiling of 2°C for eventual warming. Once such targets are set, the social cost problem becomes one of identifying the least-cost way to achieve the target. The discount rate chosen affects the timing of the cutbacks, but their cumulative magnitude is determined exogenously given the climate target rather than endogenously as a function of damage avoided and abatement cost. Even in this approach it would be important to calculate the best estimate of quantifiable non-catastrophic damages avoided, as they would likely cover a considerable portion of abatement costs if not the full amount. Given marginal abatement cost along the least-cost path, the proper price to use for the social cost of carbon is by definition the marginal abatement cost identified for that path.

It turns out that any extra cost paid for this insurance approach may be quite small even when compared to a supposed optimal path using more conventional discounting. Thus, in Nordhaus' (2008) results using the latest version of the DICE model, the difference between the future path of per capita consumption in his optimal path and in a path adhering to a 2°C ceiling (p. 209) is, as Tom Schelling tends to say, no wider than the lead of the pencil being used to draw the graph. The present value of abatement cost in his preferred optimal path that allows eventual warming to reach 3.5°C is a tiny 0.11

percent of the present value of future world product. If instead the 2°C limit is observed, the present value of abatement cost rises to 0.57 percent of world product (Cline, 2010a). The additional insurance costs 0.46 percent of the present value of world product over the next two centuries. That ought to be a bargain if one gives much credence at all to the various catastrophe scenarios. Similarly, in the EMF-22 projections reported in the Interagency review, limiting atmospheric concentrations to 550 ppm CO_2-equivalent would involve abatement costs amounting to only 0.66 percent of world product in 2030 and 1.3 percent in 2100 (p. 16). The insurance approach would thus seem to recommend that the Interagency group include as at least one variant a social cost of carbon path set equal to the marginal abatement cost along either the 550 ppm path or a 2°C ceiling path.

Workshop Issues

I look forward to the discussions in this workshop. Many questions seem relevant for an update of damage valuation. What do the experts now say about storm damage given the experience of Katrina? Was the Fourth Assessment Report of the IPCC understating the pace of likely sea-level rise in light of new evidence? How does the FUND model's finding of initial benefits rather than damages for up to 3°C warming square with Meinhausen's eventual loss of the Greenland ice sheet with only 2°C warming? Where do the agricultural estimates now stand? My own take in my 2007 book was that by the 2080s the losses in agricultural potential would reach about 5 to 15 percent globally, 30-40 percent in South Asia, and 20-25 percent in Africa and Latin America, depending on whether carbon fertilization is included (Cline, 2007). There is also a new category that I hope will be discussed in the session on health impacts: the adverse effect of warming on labor productivity in outdoor sectors in warm climates (Kjellstrom et al, 2008). World Bank modeling of climate policy applies large damage effects in this category (van der Mensbrugghe and Roson, 2010). I would be interested in whether participants in this workshop agree.

Bottom Line

Let me conclude by returning to where I began: I welcome the February report of the Interagency Working Group as a good start. I take some comfort from the fact that for the first two decades, its path for the social cost of carbon is broadly consistent with the Congressional Budget Office (CBO, 2009) estimates of the allowance price for carbon dioxide – or marginal abatement cost -- along the abatement path in the Waxman-Markey bill passed by the House of Representatives in 2009. That bill would have cut US emissions by 83 percent below 2005 levels by 2050, arguably enough to be consistent with global abatement close to what is needed for limiting warming to a range of 2 to 3 degrees C. Thus, the central Interagency estimate of the social cost of carbon dioxide is $26 per ton in 2020 and $33 in 2030; the CBO allowance price for Waxman-Markey is $25 in 2020 and $40 in 2030 (p. 11). However, in later periods the Interagency estimate falls increasingly short of would be needed under Waxman-Markey: $39 versus $70 per ton in 2040 and $45 versus $120 in 2050. I would suggest that given this growing discrepancy, EPA enforcement should take special care when applying the Interagency social cost estimates in decisions affecting new plant equipment designed to be in operation longer than 20 years.

This being said, it does seem to me that more attention to catastrophic considerations and a revisiting of the discounting issue, including the use of TIPs as a guide to the pre-tax consumption discount rate, are likely to lead to a higher path of the social cost of carbon than estimated by the Interagency group in its February report. It is also the case, however, that sooner rather than later it will be necessary to adopt comprehensive legislation on greenhouse gas abatement. When that is done, the American public will no longer have to rely so heavily on the EPA to sort out the right social price of carbon, because their elected representatives will implicitly have made that decision for them by setting the terms of the climate legislation. Super-contingent evaluation will have taken place through the democratic process. In the meantime, political economy could plausibly counsel against any massive shocks in the Interagency Group's revisions of the social cost of carbon. The EPA will need to walk a tightrope between placing too low an estimate that risks the environment, on the one hand, and on the other, placing so high an estimate that it provokes congressional blocking measures (such as threats to block public debt bills unless they include a clause removing the agency's authority to enforce greenhouse gas abatement). Continuing to build on the professional and rigorous approach already begun seems likely to help assure that this narrow path can be successfully followed.

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Tropical Cyclones and Climate Change

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1. Introduction

This extended abstract addresses the question of climate change impacts on tropical cyclones, with a focus on: 1) the detection or attribution of past anthropogenic changes in tropical cyclone activity and 2) projected changes by the late 21st century under the IPCC A1B scenario. A greater emphasis is placed on Atlantic hurricanes than other basins.

In February 2010, a World Meteorological Organization (WMO) Expert Team on Climate Change Impacts on Tropical Cyclones published an assessment of "Tropical Cyclones and Climate Change" in Nature Geoscience[1]. The WMO assessment forms the basis for the "consensus" or "best estimate" views in this abstract, which are presented in sections 2-3. Speakers at the workshop were also asked to address the range of possible outcomes. The ranges of future projections presented in the WMO assessment were not intended be interpreted as the range of *possible* future changes. Therefore, in sections 4-5, I expand on some issues which were not explicitly covered by the WMO team report, particularly in section 5 with some speculations concerning a wider range of possible tropical cyclone changes. These comments on the wider range of possible impacts and on statistical vs. dynamical models (section 4) represent my personal views and not necessarily those of the WMO team.

2. Detection of a climate change in tropical cyclones?

The term *climate change detection* as used in this abstract refers to a change which is anthropogenic in origin and is sufficiently large that the signal clearly rises above the background "noise" of natural climate variability (with the "noise" produced by internal climate variability, volcanic forcing, solar variability, and other natural forcings). As noted in IPCC AR4[2], the rise of global mean temperatures over the past half century is an example of a detectable climate change; in that case IPCC concluded that most the change was very likely attributable to human-caused increases in greenhouse gas concentrations in the atmosphere.

In the case of tropical cyclones, the WMO team concluded[1] that it was uncertain whether any changes in past tropical cyclone activity have exceeded the levels due to natural climate variability. While some long (century scale) records of both Atlantic hurricane and tropical storm counts show significant rising trends, further studies have pointed to potential problems (e.g., likely missing storms) in these data sets due to the limited density of ship traffic in the pre-satellite era. After adjusting for such changes in observing capabilities for non-landfalling storms, one study[3] found that the rising trend in tropical storm counts was no longer statistically significant. Another study[4] noted that almost the entire trend in tropical storm counts was due to a trend in short-duration (less than two days) storms, a feature of the data which those authors interpreted as likely due in large part to changes in observing capabilities.

A global analysis of tropical cyclone intensity trends over 1981-2006 found increases in the intensities of the strongest tropical cyclones, with the most significant changes in the Atlantic basin[5]. However, the short time period of this dataset, together with the lack of "Control run" estimates of internal climate variability of TC intensities, precludes a climate change detection at this point. The intensity data also have uncertainties, particularly in the Indian Ocean where the satellite record is less consistent over time.

3. Tropical Cyclone Projections for the Late 21st Century

Based on available studies, the WMO team concluded[1] the following regarding tropical cyclone projections for the late 21st century, assuming that the large-scale climate changes are as projected by the IPCC AR4 A1B scenario (quoted from Box 1 of the Nature Geoscience report):

> "**Frequency.** It is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged owing to greenhouse warming. We have very low confidence in projected changes in individual basins. Current models project changes ranging from -6 to -34% globally, and up to +/-50% or more in individual basins by the late twenty-first century.
>
> **Intensity.** Some increase in the mean maximum wind speed of tropical cyclones is likely (+2 to +11% globally) with projected twenty-first century warming, although increases may not occur in all tropical regions. The frequency of the most intense (rare, high-impact) storms will more than not increase by a substantially larger percentage in some basins.
>
> **Rainfall.** Rainfall rates are likely to increase. The projected magnitude is on the order of +20% within 100 km of the tropical cyclone centre.
>
> **Genesis, tracks, duration, and surge flooding.** We have low confidence in projected changes in tropical cyclone genesis-location, tracks, duration, and areas of impact. Existing model projections do not show dramatic large-scale changes in these features. The vulnerability of coastal regions to storm-surge flooding is expected to increase with future sea-level rise and coastal development, although this vulnerability will also depend on future storm characteristics."

While the WMO team judged that a substantial increase in the frequency of the most intense storms over the 21st century is more likely than not globally, their confidence in this finding was limited, since the model-projected change results from a competition between the influence of increasing storm intensity and decreasing overall storm frequency. An example of such a change projected for the Atlantic basin is found in a recent downscaling study[6] by Bender et al. (GFDL) using an operational (9 km grid) hurricane prediction model. This downscaling framework projects a doubling in the frequency of Atlantic category 4-5 hurricanes over the 21st century (A1B scenario) using an 18-model average climate change signal. However, when four of the 18 individual models were downscaled, three showed an increase and one a decrease in category 4-5 frequency. Differences in regional SST projections in the various climate models appeared to be important for producing this large range of projections, implying that uncertainties in future regional SST pattern changes must be narrowed to reduce the uncertainty in Atlantic hurricane projections. The study also presented preliminary estimates of the climate-induced change in hurricane damage potential for the Atlantic basin (+28% by 2100 for the 18-model average, with a range of -54% to +71% for the 4 individual models runs). These damage potential projections do not include important influences such as sea level rise, coastal development, and societal adaptation.

4. Methodologies for projecting Tropical Cyclone changes: statistical vs. dynamical models

The projections in the previous section rely heavily on dynamical models including global climate models, higher resolution global atmospheric models forced by SSTs from global climate models, or even higher resolution regional downscaling models. In addition, some studies employed either statistical/dynamical hybrid models or theoretical intensity models. The WMO report also discussed an example of using purely statistical (correlation) methods to project late 21st century Atlantic hurricane power dissipation. In that case, two alternative statistical models of hurricane activity vs SST, both of which perform comparably during the historical period, give dramatically different projections of late 21st century activity, with the projection based on local tropical Atlantic SST showing a dramatic increase of about 300% in power dissipation by 2100. The second statistical approach (relative SST) projects much smaller changes in Atlantic power dissipation by 2100—a scenario strongly favored by current dynamical models. The differences between various dynamical model projections seem to be explained[7] in large part by differences in tropical Atlantic warming relative to the rest of the tropics as projected by the parent climate model used to drive the downscaling model.

The example for Atlantic power dissipation illustrates how dynamical and statistical downscaling techniques, or different statistical approaches, can differ substantially in their projections of the tropical cyclone response to a given climate change scenario. In terms of general modeling approaches, both dynamical modeling and statistical modeling techniques can provide complementary approaches and are worthy of pursuit, although each has its limitations, and results using either approach should be interpreted with due caution. Dynamical modeling attempts to use fundamental physical laws such as the equations of motion and the first law of thermodynamics, integrating systems of these equations forward in time using computer models. One reason this approach is often favored in the case of climate change is that one assumes that the fundamental laws are more likely to be applicable in a changed climate than empirical relations derived by training a statistical model on past climate data alone.

5. Some speculations on the range of possible outcomes

Here I regard the projections in section 3 from the WMO report as consensus statements based on available studies. However, it is possible that more dramatic future changes could occur over the 21st century. While, in my opinion, these more dramatic changes remain speculative, they are at least plausible enough to merit discussion here.

First, it is possible that 21st century changes in tropical cyclones will be less potentially damaging than the scenarios outlined in the projections section. For example, some studies suggest that TC activity in some basins, such as the NW Pacific and North Atlantic, could shift eastward away from current landfalling regions and thus perhaps reduce the percentage of storms that make landfall in major population regions. Global climate transient sensitivity or sea level rise could be at the low end, or even lower than, the range shown in IPCC AR4. Future greenhouse gas concentrations could be toward the lower end or lower than IPCC AR4 scenarios. Alternatively, it is also possible that the reverse could be true in these cases, i.e., that transient climate sensitivity, future greenhouse gas concentrations, sea level rise, and so forth could be higher than expected, or even that storm tracks could shift systematically more toward major landfalling regions, in contrast to a number of current projections.

In addition to these contributors to uncertainty, for the remainder of this section, I will focus on other more novel mechanisms under which future changes could imply substantially greater damage potential than the projections of the WMO report.

Vertical profile of temperature change. A common characteristic of climate model projections of greenhouse warmed climates is an increase in the temperature change with height, such that the upper troposphere about 4 miles above the earth's surface warms more than near the surface. This enhanced warming with height is one of the key factors leading to relatively modest changes in hurricane activity in future climate projections. If the warming were instead uniform with height through the troposphere, the atmosphere would become more unstable and much more conducive to hurricane activity over time, and the resulting increases in intensity could be several times larger than those currently projected. Interestingly, observed vertical profiles of air temperature changes since about 1980 using radiosondes and some satellite records actually show a relatively uniform warming with height through the troposphere. However, as argued by Santer et al.[8], such a change is not only inconsistent with climate models and with the notion that the tropical atmospheric remain close to a moist adiabatic profile, but such as uniform change also differs from the vertical profile of year-to-year fluctuations in temperature, where climate models and observations agree that an such temperature variations have an amplified signal with height in the troposphere. Further, Allen and Sherwood[9] argue that the observed destabilizing temperature trends are inconsistent with temperature trends inferred from wind fields. Therefore I consider it more likely that data problems with the radiosonde and satellite temperature datasets have led to unreliable observed temperature trend profiles that falsely indicate a substantial destabilization of the tropical atmosphere since 1980. Of course it remains important to confirm this assertion with further studies and to maintain a vigilant observing network to monitor the vertical profile of tropical temperatures and TC activity as the planet continues to warm.

Lower stratospheric temperatures. A variant on the theme of vertical profile of temperature changes is the recent study of Emanuel[10], who reports that a cooling trend in the lower stratospheric temperatures in recent decades implies an increase in potential intensity of hurricanes in the Atlantic. According to his statistical/dynamical model, this has further caused an increase in Atlantic tropical storm numbers. While the lower stratospheric temperature decrease remains a subject of further investigation as to its veracity and cause, preliminary results with another (dynamical) model from GFDL (G. Vecchi, personal communication) suggest that lower stratospheric temperatures do not affect tropical storm counts substantially in that model. Further work is needed to better constrain lower stratospheric and upper tropospheric temperature changes, their causes, and their impact on tropical cyclones in general. For example, one can speculate that ozone changes and related atmospheric effects could have affected tropical upper tropospheric temperatures enough to change tropical cyclone activity substantially. If so, this mechanism would have implications for past and future (projected) changes in Atlantic hurricane activity. For example, if it turns out that ozone depletion contributed substantially to the increased Atlantic hurricane activity in recent decades, then the higher activity levels since 1995 could be more persistent than expected on the basis of typical internal variability (Atlantic Multidecadal Oscillation) arguments. Those internal variability arguments typically suggest that hurricane activity will likely return toward pre-1995 levels sometime in the next few decades. In any case, the potential links between lower stratospheric and/or upper tropospheric temperatures, climate forcings, and hurricane activity mentioned here remain speculative.

Impact of Tropical Cyclones on Ocean Heat Transport. Previous work by Emanuel had suggested that tropical cyclones could influence the climate system through changes in the rate of vertical oceanic mixing, leading to changes in the global oceanic heat transport. More recent studies have estimated that this influence on heat transport is confined mainly to the tropics. For example, Jansen et al.[11] estimate that TC cause less than 10% of the global poleward heat transport.

From a paleoclimate perspective, changes in tropical cyclone activity have been proposed as a key mechanism for maintaining the ‘equable’ climates of the early Pliocene (3 to 5 million years ago), when some geologic proxy indicators suggest that the warm tropical SST region was markedly expanded poleward and the eastern equatorial Pacific cold tongue was absent. Federov et al.[12] simulated large increases in tropical cyclone activity during this time, and suggested that the very different temperatures of that time were linked to tropical cyclone feedbacks on climate. Enhanced tropical cyclone activity in their downscaling in the eastern Pacific eventually leads, in their climate model simulations, to permanent El Niño conditions. While the simulated changes in TC activity and in sea surface temperatures in their study are dramatic, the implications of their simulations for climate changes over the next century or so remain speculative.

6. Key research needs going forward

Among the key research needs going forward is the urgent need to have consistent, homogeneous long-term records of hurricane statistics (for trend and climate change assessment) and the need to narrow uncertainties in future sea level rise and regional SST pattern changes that drive regional tropical cyclone changes. Improved quantification or reduction of uncertainty in SST pattern projections will likely depend on reducing uncertainties in cloud feedback, aerosol forcing, and possibly in coupled ocean-atmosphere interaction, which remain central problems in climate change research. Continued monitoring of tropical cyclone activity globally for emergence of trends, as well as further research concerning the vertical structure of the atmospheric temperature changes and ocean mixing effects by tropical cyclones are all prudent measures for earlier detection and/or anticipation of future "surprises" in the hurricane/climate realm.

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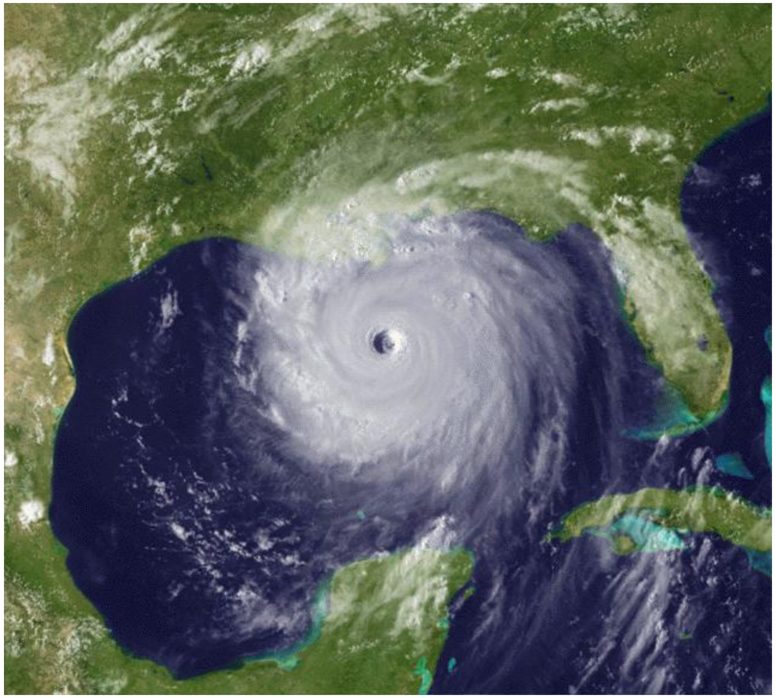
Tropical Cyclones and Climate Change



Hurricane Katrina (2005), damage estimate: ~$US125 Billion

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nature geoscience

REVIEW ARTICLE

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Tropical cyclones and climate change

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Overview of Assessments

Climate Change Detection and Attribution:

- It remains uncertain whether past changes in tropical cyclone activity exceed natural variability levels.

Projections for late 21st century:

- Likely fewer tropical storms globally (~no change to -34%), with even greater uncertainty in individual basins (e.g., the Atlantic).

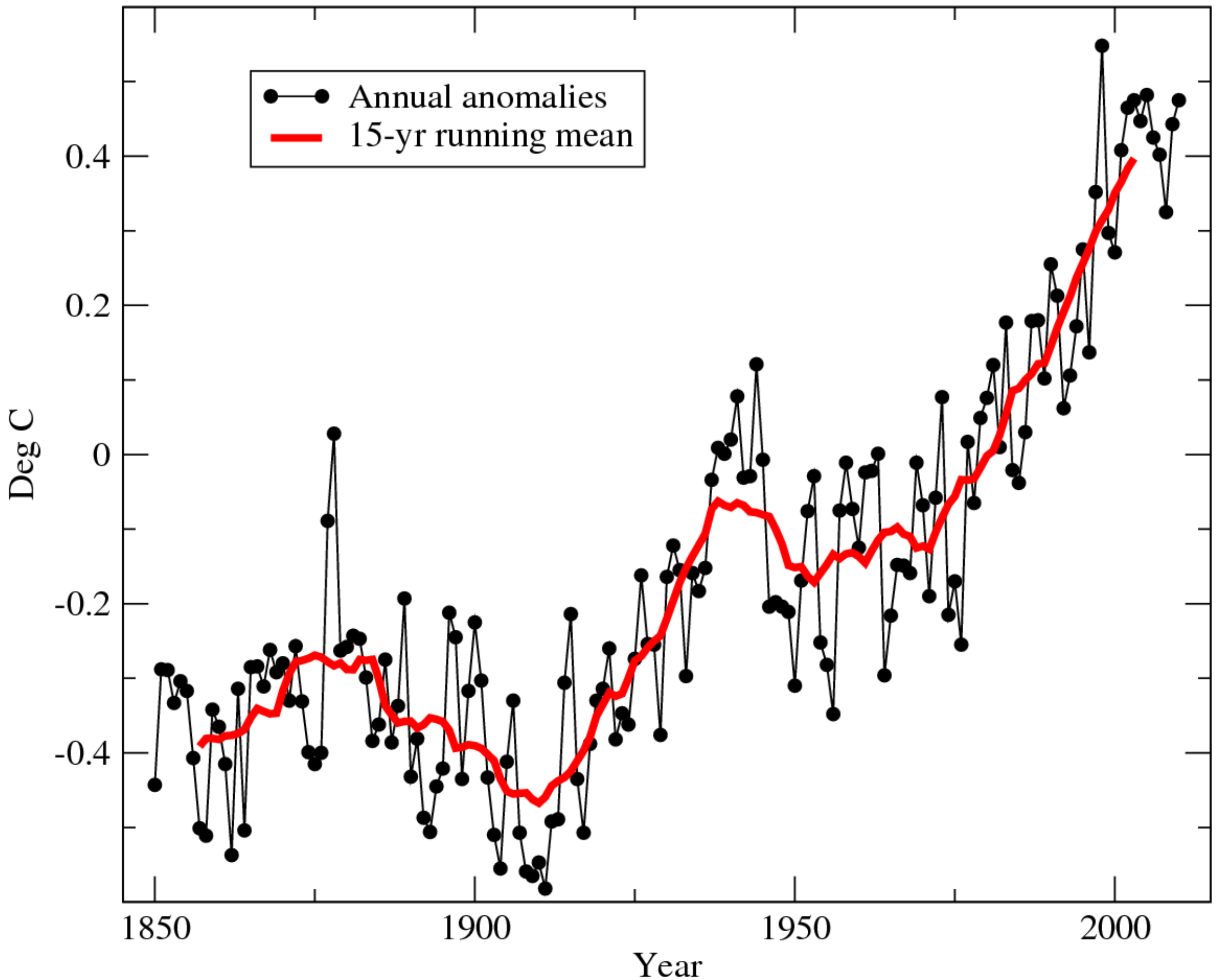
- Likely increase in average hurricane wind speeds globally (+2 to11%), though not necessarily in all basins

- More likely than not (>50% chance) that the frequency very intense hurricanes will increase by a substantial fraction in some basins

- Likely higher rainfall rates in hurricanes (roughly +20% within 100 km of storm)

- Sea level rise is expected to exacerbate storm surge impacts even assuming storms themselves do not change.

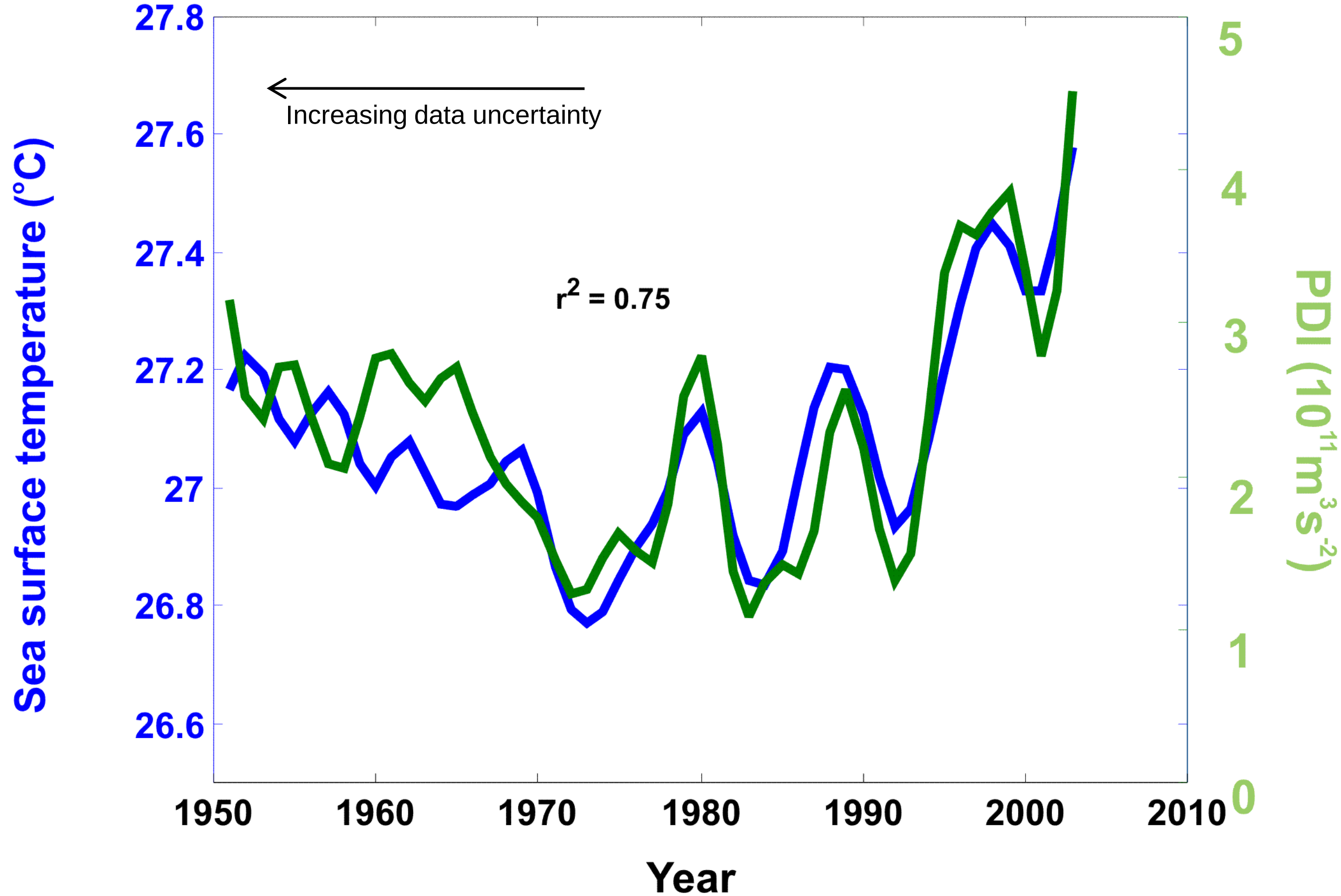
HadCRUT3 global mean temperature anomalies (1850-2010)



Fri Jan 21 13:18:44 2011

Source: Climatic Research Unit. http://www.cru.uea.ac.uk/cru/data/temperature/

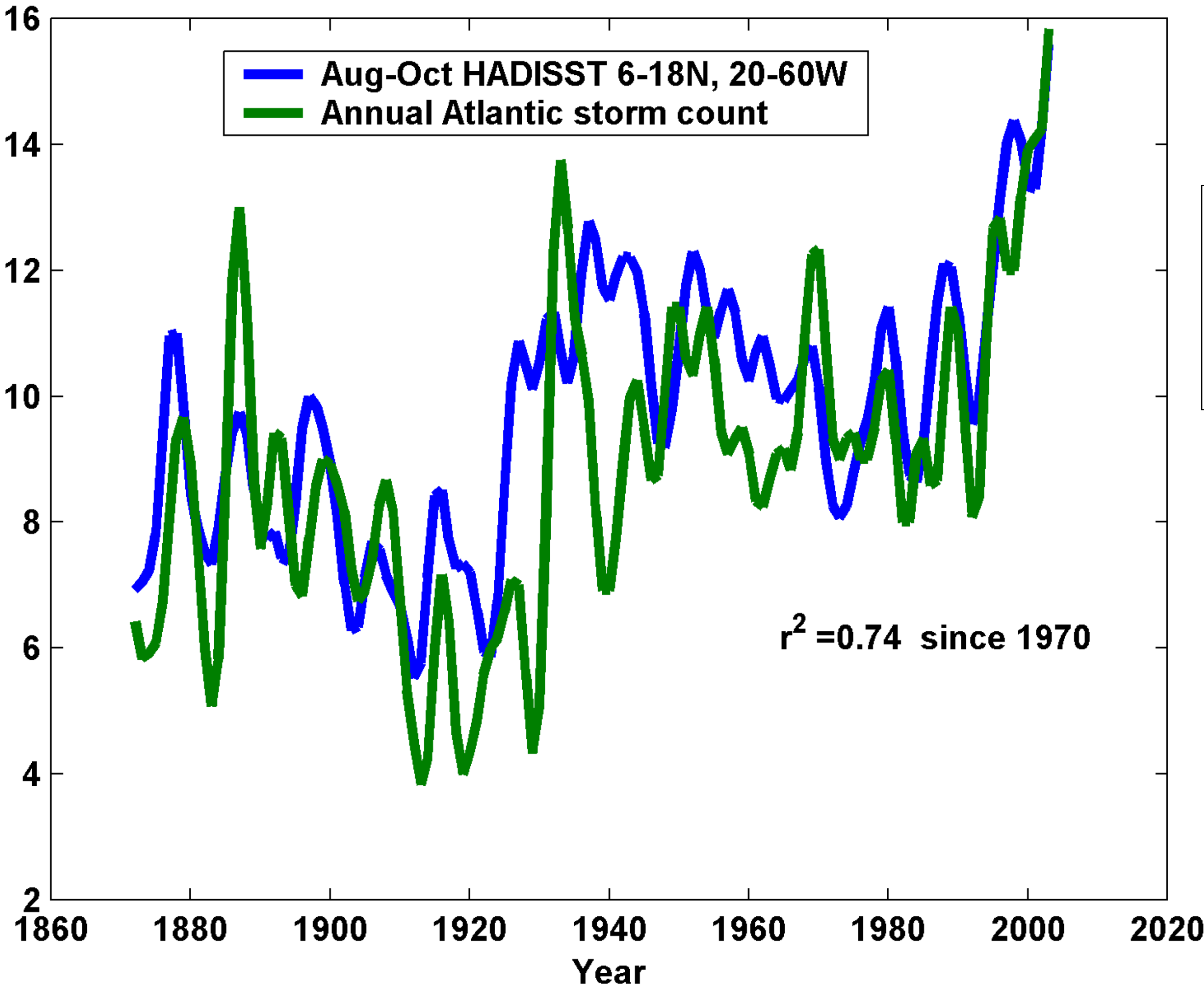
There is some recent evidence that overall Atlantic hurricane activity may have increased since in the 1950s and 60s in association with increasing sea surface temperatures…



PDI is proportional to the time integral of the cube of the surface wind speeds accumulated across all storms over their entire life cycles.

Source: Kerry Emanuel, J. Climate (2007).

The frequency of tropical storms (low-pass filtered) in the Atlantic basin since 1870 has some correlation with tropical Atlantic SSTs

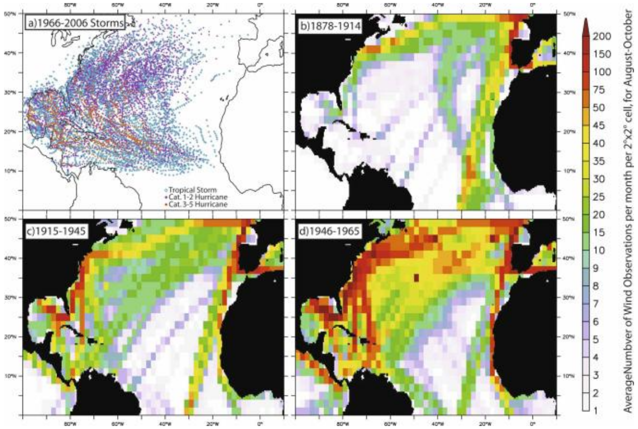


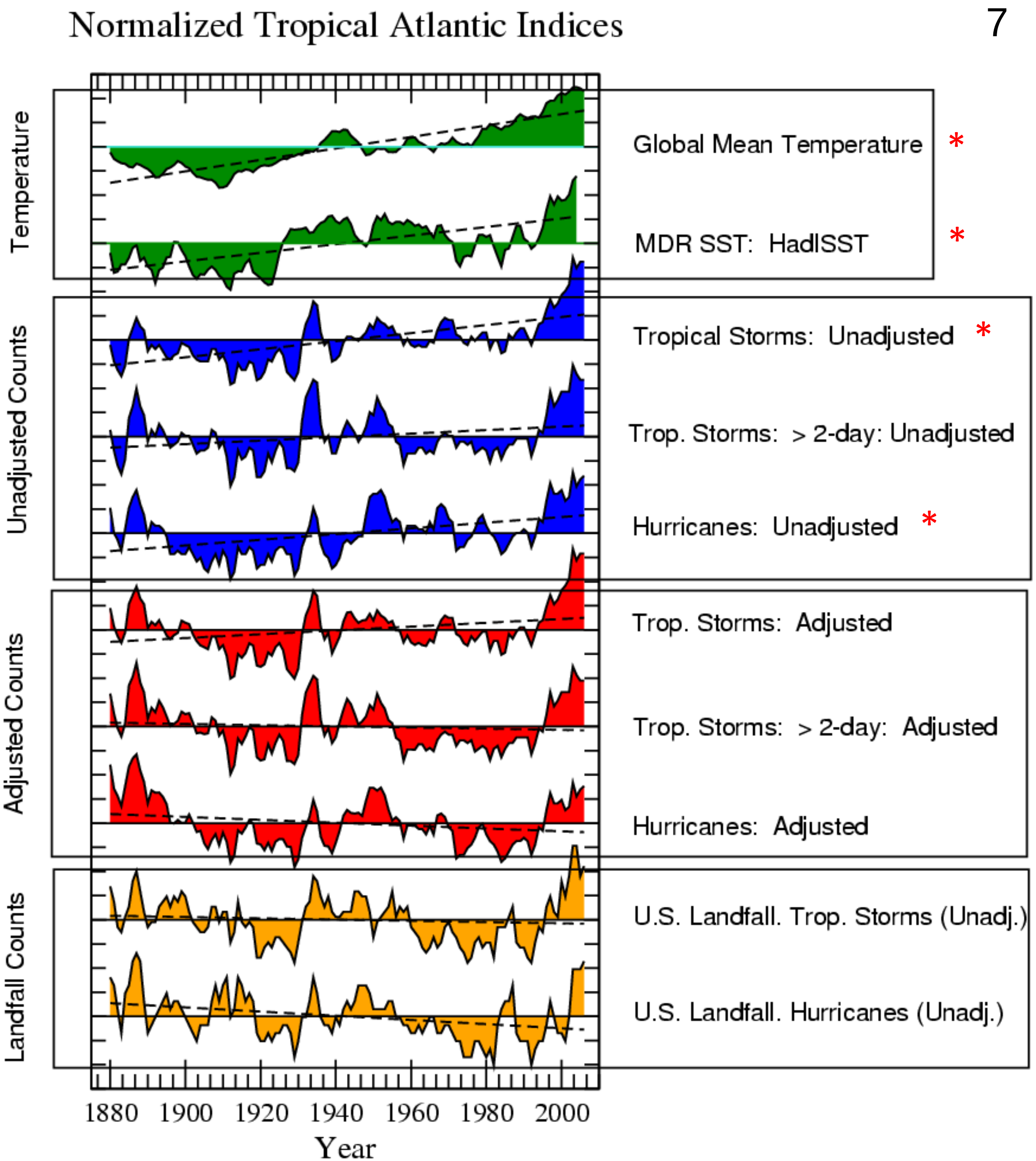
But is the storm record reliable enough for this?

Source: Emanuel (2006); Mann and Emanuel (2006) EOS. See also Holland and Webster (2007) *Phil. Trans. R. Soc. A*

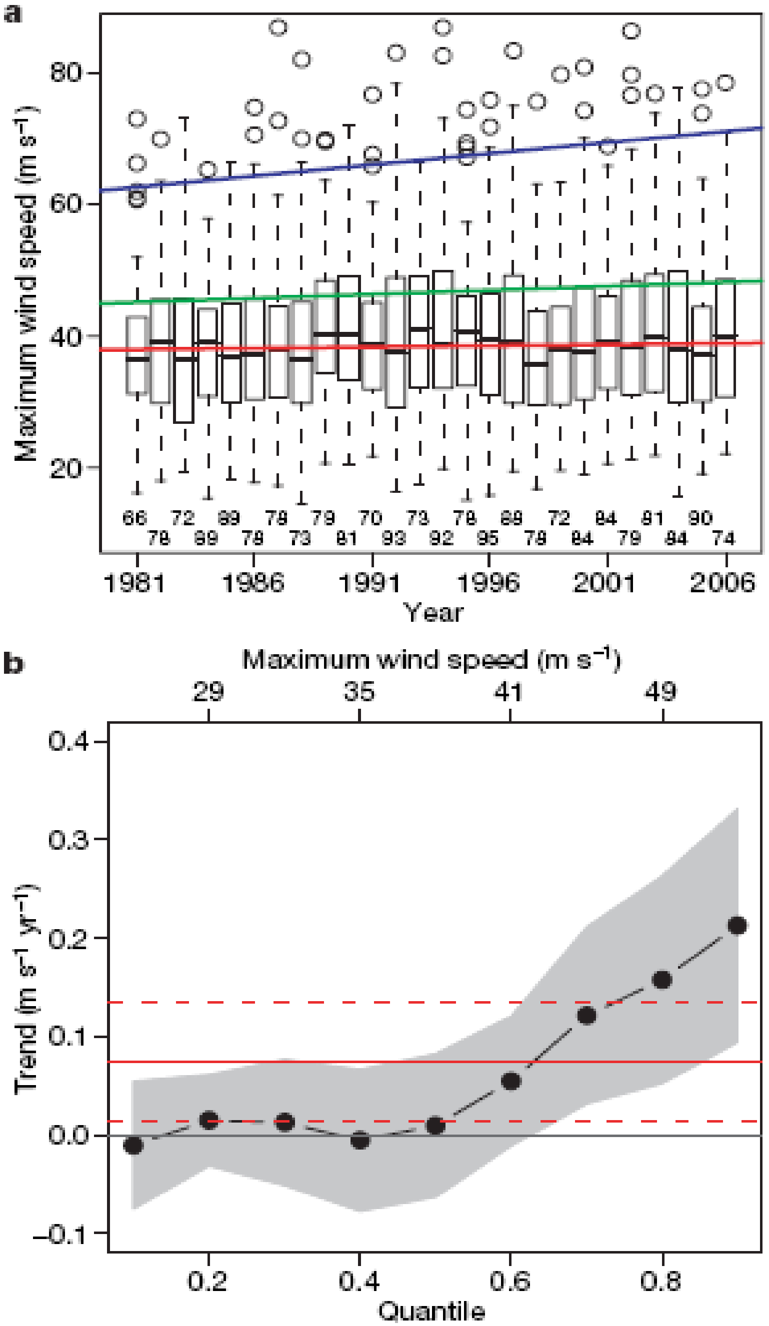
* => Significant at p=0.05

Adjustments to storm counts based on ship/storm track locations and density





Sources:
Vecchi and Knutson (2008)
Landsea et al. (2009)
Vecchi and Knutson (in press)



Global Tropical Cyclone Intensity Trends

There is some statistical evidence that the strongest hurricanes are getting stronger. This signal is most pronounced in the Atlantic. However, the satellite-based data for the global analysis are only available for 1981-2006.

Quantile regression computes linear trends for particular parts of the distribution. The largest increases of intensity are found in the upper quantiles (upper extremes) of the distribution.

Source: Elsner et al., *Nature,* 2008

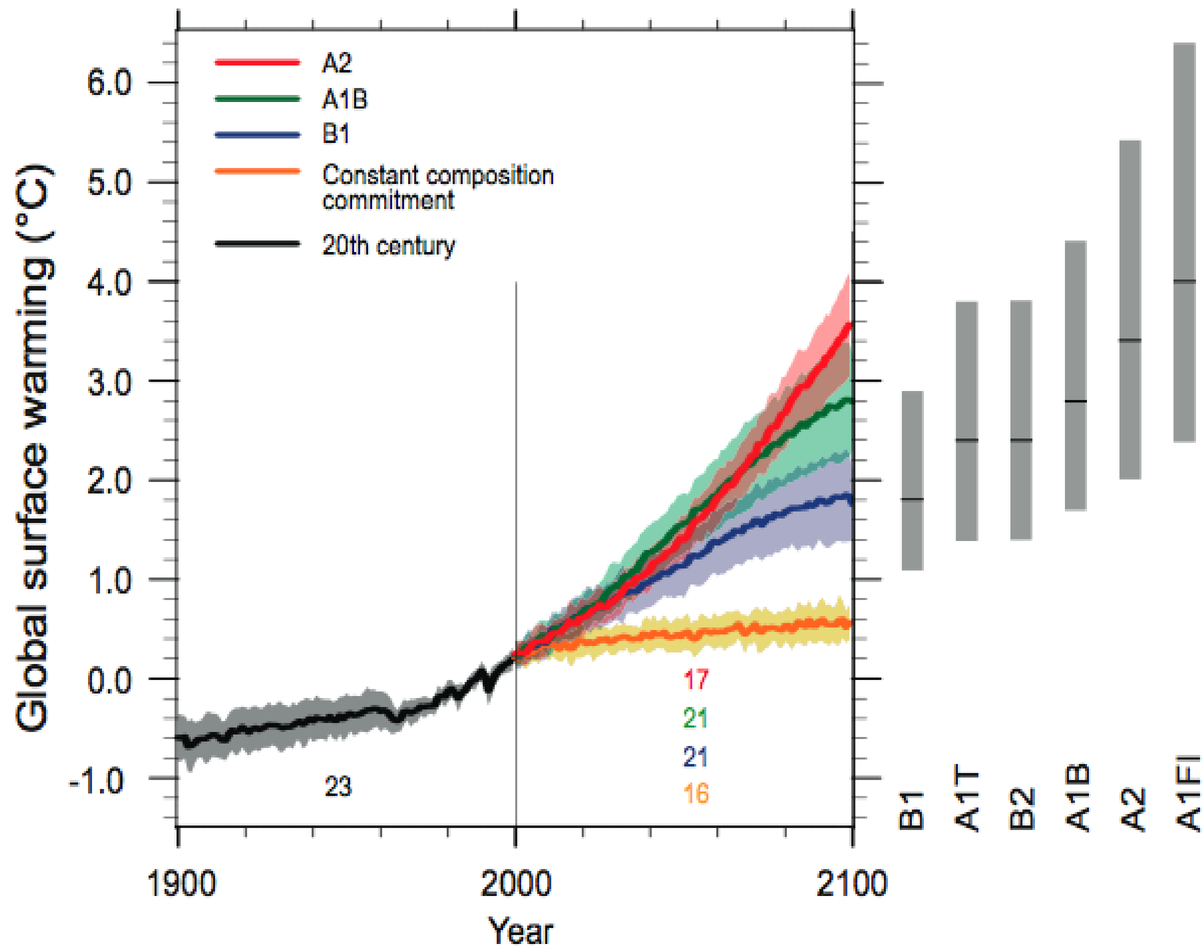
IPCC Projections of Future Changes in Climate

Global Mean Temperature Change

IPCC best estimates (with *likely* ranges):

Low scenario (B1):
1.8 C (1.1 - 2.9 C)

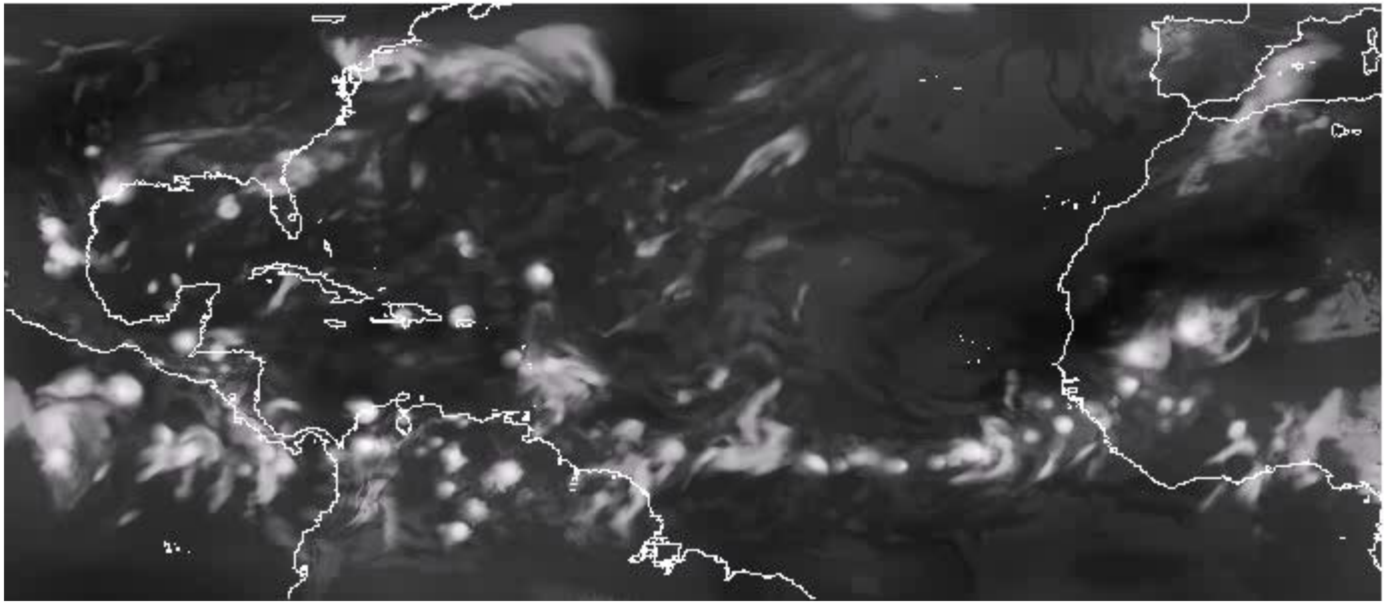
High scenario (A1FI):
4.0 C (2.4 - 6.4 C)

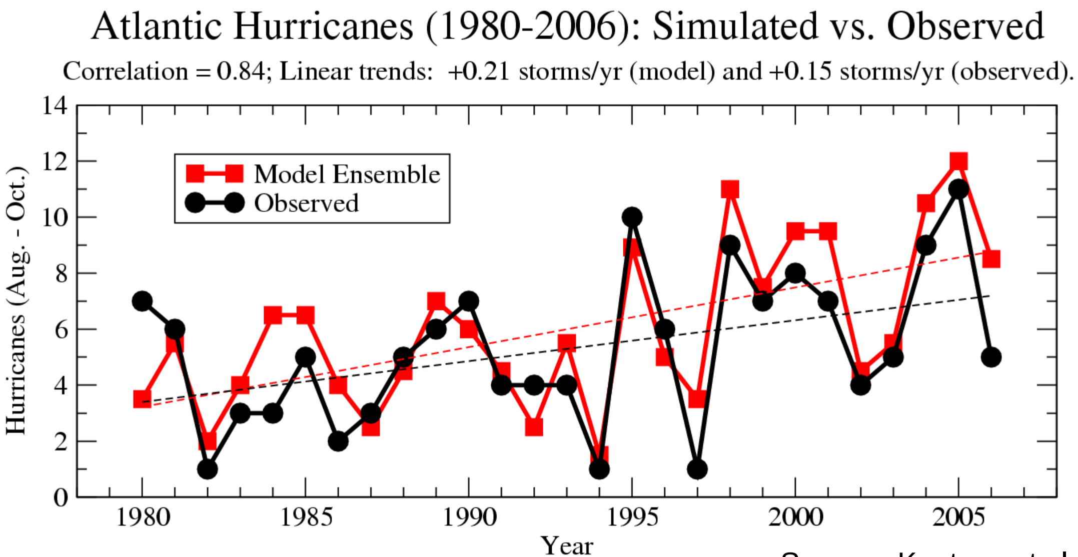


Source: IPCC 4th Assessment Report. Used with permission.

Zetac Regional Model reproduces the interannual variability and trend of Atlantic hurricane counts (1980-2006)

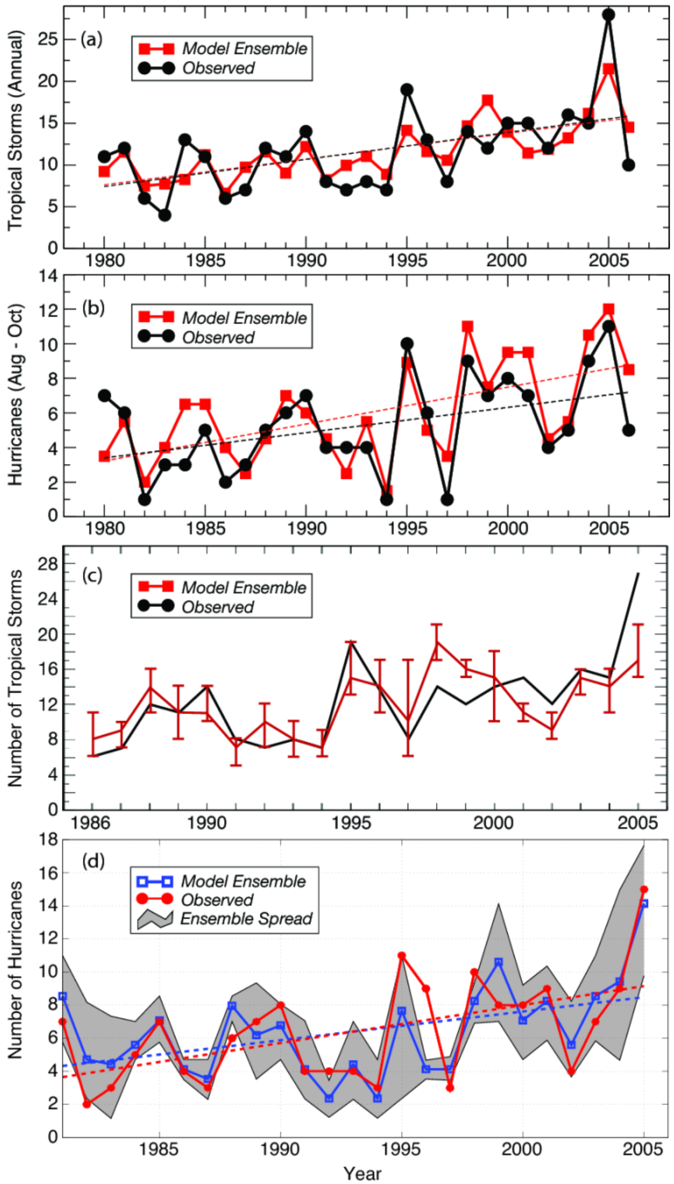
18-km grid model nudged toward large-scale (wave 0-2) NCEP Reanalyses





Source: Knutson et al., *2007*, Bull. Amer. Meteor. Soc.

Simulating past variability in Atlantic tropical cyclone activity



Progress has been made in developing dynamical and statistical/dynamical models for seasonal tropical cyclone frequency.

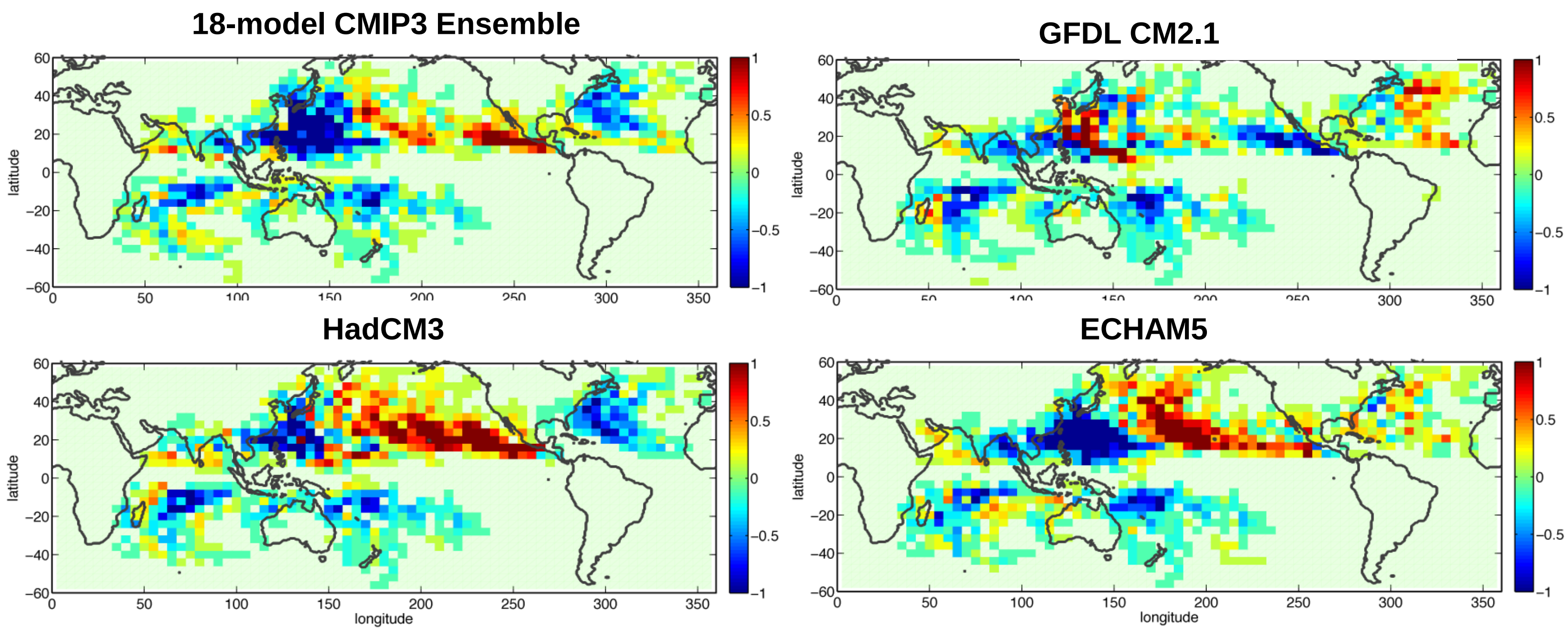
Left: examples for the Atlantic basin, using high resolution atmospheric models; regional dynamical downscaling models; and statistical/dynamical techniques.
(a) and (b) use NCEP Reanalysis.
(c) and (d) use only SSTs.

<u>Current question</u>: Is the cooling of tropopause transition layer (TTL) temperatures crucial for simulating the Atlantic trend in TCs over this period?

Source: Knutson et al., Nature Geoscience (2010).

Projected Changes in Regional Hurricane Activity

GFDL 50-km HIRAM, using four projections of late 21st Century SSTs.



Red/yellow = increase
Blue/green = decrease

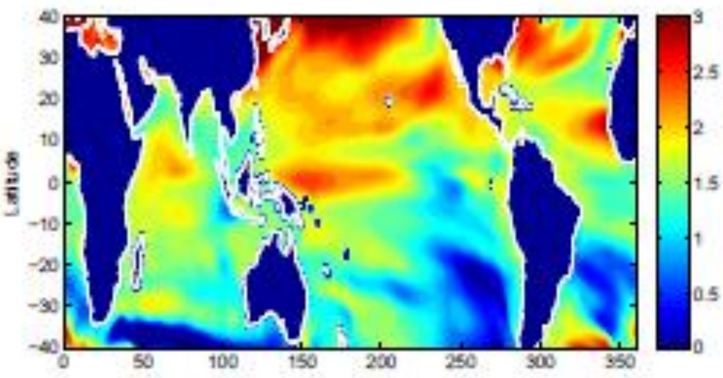
Unit: Number per year

- Regional increases/decreases much larger than global-mean.
- Pattern depends on details of SST change.

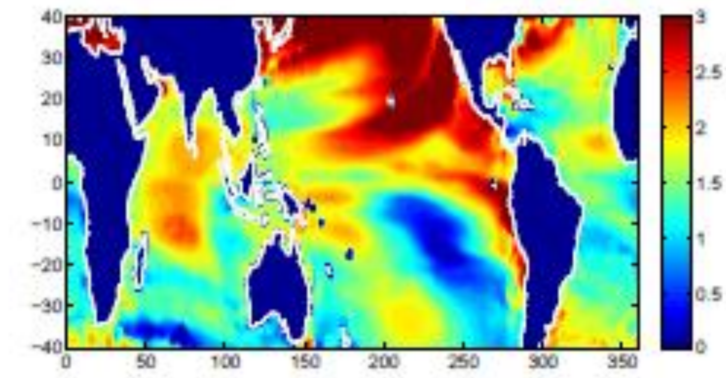
Source: Courtesy Ming Zhao, GFDL. Adapted from Zhao, et al. (J. Climate, 2009)

Global Model Tropical Cyclone Climate Change Experiments: Use A1B Scenario late 21st century projected SST changes from several CMIP3 models

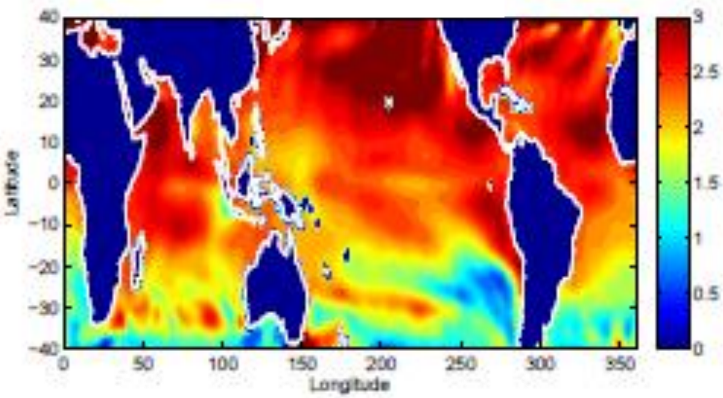
GFDL CM2.1



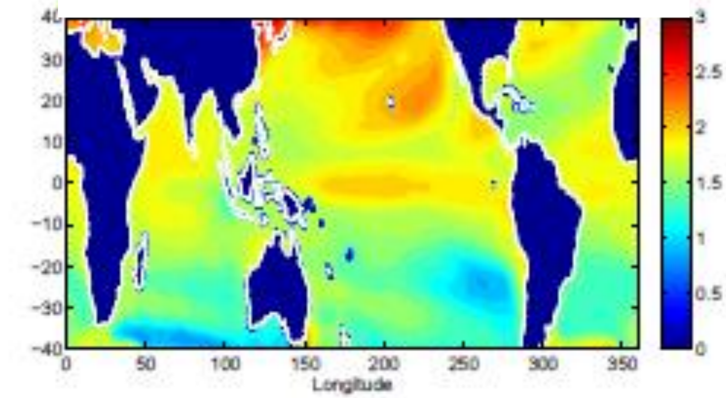
HadCM3



ECHAM5



CMIP3 18-model Ensemble



Source: Zhao, Held, Lin, and Vecchi (J. Climate, 2009)

Unit: Deg C

TABLE S1. TC Frequency Projections												
Reference	Model/type	Resolution/	Experiment	Basin								
				Global	NH	SH	N Atl.	NW Pac.	NE Pac	N Ind	S Ind	SW Pac
Tropical Storm Frequency Changes (%)												
Sugi et al. 2002 (ref 36)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	-34	-28	-39	+61	-66	-67	+9	-57	-31
McDonald et al. 2005 (ref 53)	HadAM3 Timeslice	N144 L30 (~100km)	15y IS95a 1979-1994 2082-2097	-6	-3	-10	-30	-30	+80	+42	+1 0	-18
Hasegawa and Emori 2005 (ref 54)	CCSR/NIES/FRC GC timeslice	T106 L56 (~120km)	5x20y at 1xCO2 7x20y at 2xCO2					-4				
Yoshimura et al. 2006 (ref 55)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	-15								
Oouchi et al. 2006 (ref 10)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	-30	-28	-32	+34	-38	-34	-52	-28	-43
Chauvin et al. 2006 (ref 11)	ARPEGE Climat Timeslice	~50 km	Downscale CNRM B2 Downscale Hadley A2				+18 -25					
Stowasser et al. 2007 (ref 56)	IPRC Regional		Downscale NCAR CCSM2, 6xCO2					+19				
Bengtsson et al. 2007 (ref 23)	ECHAM5 timeslice	T213 (~60 km)	2071-2100, A1B		-9		-8	-20	+4	-26		
Bengtsson et al. 2007 (ref 23)	ECHAM5 timeslice	T319 (~40 km)	2071-2100, A1B		-12		-13	-28	+7	-51		
Emanuel et al. 2008 (ref 21)	Statistical-deterministic	---	Downscale 7 CMIP3 mods.: A1B, 2180-2200 Average over 7 models	-7	-4	-14	+2	+6	-5	-8	n/a	n/a
Knutson et al. 2008 (ref 22)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100				-27					
Leslie et al. 2007 (ref 57)	OU-CGCM with high-res. window	Up to 50 km	2000 to 2050 control and IS92a (6 members)									~0
Gualdi et al. 2008 (ref 34)	SINTEX-G coupled model	T106 (~120 km)	30 yr 1xCO2, 2xCO2, 4xCO2	-16 (2x) -44 (4x)			-14	-20	-3	-13	-14	-22
Semmler et al. 2008 (ref 58)	Rossby Centre regional model	28 km	16 yr control and A2, 2085-2100				-13					
Zhao et al. 2009 (ref 12)	GFDL HIRAM timeslice	50 km	Downscale A1B: CMIP3 n=18 ens. GFDL CM2.1 HadCM3 ECHAM5	-20 -20 -11 -20	-14 -14 +5 -17	-32 -33 -42 -27	-39 -5 -62 -1	-29 -5 -12 -52	+15 -23 +61 +35	-2 -43 -2 -25	-30 -33 -41 -13	-32 -31 -42 -48
Sugi et al. 2009 (ref 59)	JMA/MRI global AGCM timeslice	20 km 20 km 20 km 20 km 60 km 60 km 60 km 60 km	Downscale A1B: MRI CGCM2.3 MRI CGCM2.3 MIROC-H CMIP3 n=18 ens. MRI CGCM2.3 MIROC-H CMIP3 n=18 ens. CSIRO	-29 -25 -27 -20 -20 -6 -21 -22	-31 -25 -15 -21 -21 0 -19 -29	-27 -25 -42 -19 -17 -16 -25 -11	+22 +23 -18 +5 +58 +6 +4 -37	-36 -29 +28 -26 -36 +64 -14 +13	-39 -30 -50 -25 -31 -42 -33 -49	-39 -29 +32 -15 -12 +79 +33 -7	-28 -25 -24 -5 -22 +1 0 -18 -22	-22 -27 -90 -42 -8 -69 -36 +10

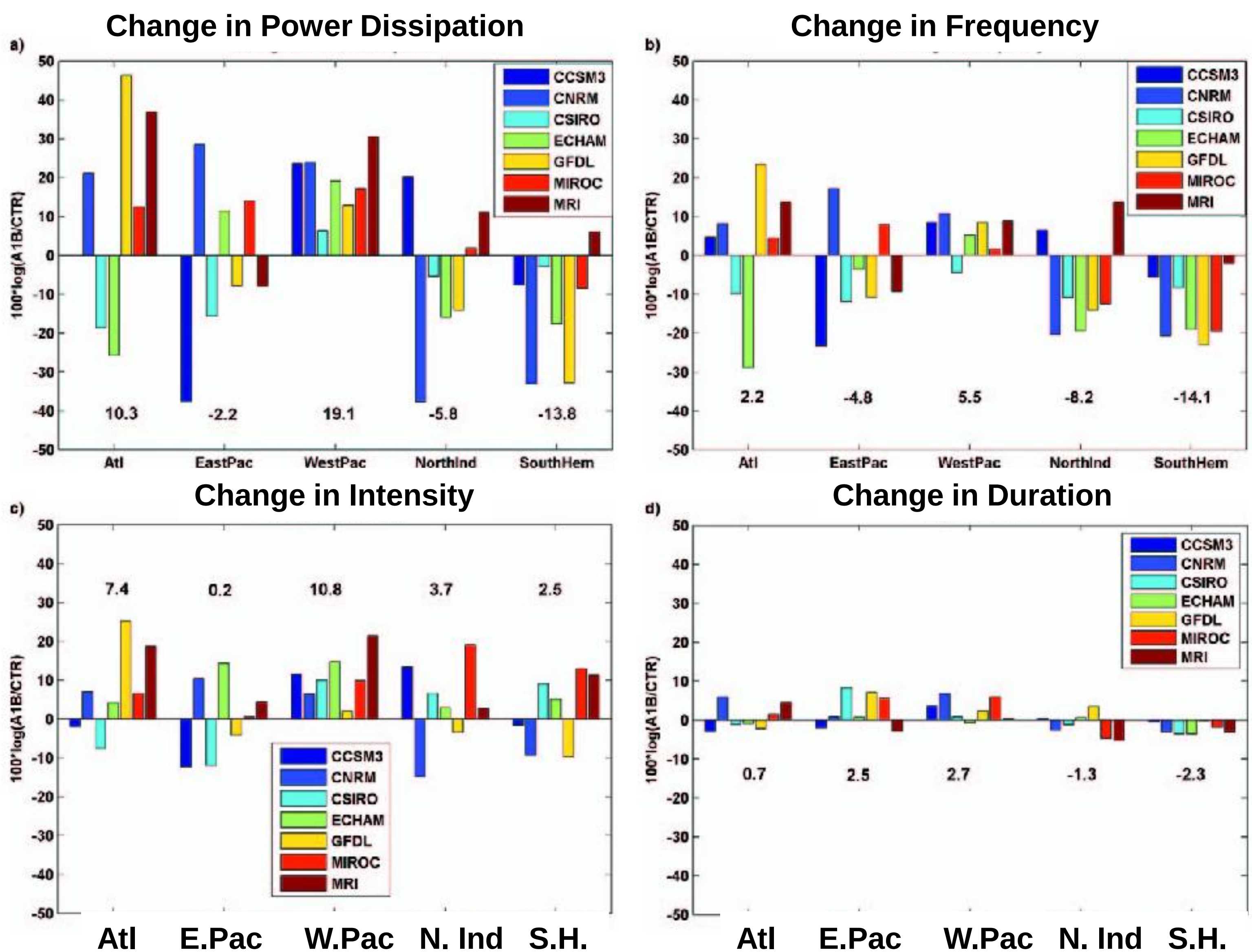
Tropical Cyclones Frequency Projections (Late 21st century) - Summary

Blue = decrease

Red = increase

Source: Knutson et al., Nature Geoscience 2010.

Statistical/Dynamical Downscaling Projections: Emanuel et al. (2008)



Source: Emanual et al. (2008) Bull. Amer. Meteor. Soc.

Tropical Cyclone Intensity Projections

Table S2. Intensity Projections: Metric/ Reference	Technique/ Model	Resolution/ Metric type	Climate Change scenario	Global	NH	SH	NAtl, NW Pac, NE Pac	N Atl.	NW Pac.	NE Pac.	N Ind.	S. Ind.	SW Pac.
Potential intensity or stat/dynamical projections (% Change)								Avg (low, high)					
Vecchi and Soden 2007 (adapted from ref 60)	Emanuel PI, reversible w/ diss. heating	Max Wind speed (%)	CMIP3 18-model A1B (100yr trend)	2.6	2.7	2.4	2.1	0.05 (-8.0, 4.6)	2.9 (-3.1, 12.6)	3.5 (-6.4 16.1)	4.4 (-3.3, 16.0)	3.7 (-7.6, 17.1)	0.99 (-8.6, 8.6)
Knutson and Tuleya 2004 (adapted from ref 9)	Potential Intensity Emanuel, reversible	Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				5.0	2.6 (-5.6, 12.6)	7.0 (-1.0, 19.6)	5.4 (-5.0, 21.9)			
Knutson and Tuleya 2004 (ref 9)	Potential Intensity, Emanuel, pseudoadiabatic	Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				7.6	6.0 (1.6, 13.2)	8.5 (2.8, 25.2)	8.2 (-3.3, 28.0)			
Knutson and Tuleya 2004 (ref 9)	Potential Intensity, Holland	Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				15.2	12.4 (-4.0, 28.9)	17.3 (9.4, 30.6)	15.8 (3.4, 42.5)			
Emanuel et al., 2008 (ref 21)	Stat./Dyn. Model	Max Wind speed (%)	CMIP3 7-model A1B (2181-2200 minus 1981-2000)	4.5		2.5	6.1	7.4	10.8	0.2	3.7		
Dynamical Model Projections (Max wind speed % change)													
Knutson and Tuleya 2004 (ref 9)	GFDL Hurricane Model	9 km grid inner nest	CMIP2+ +1%/yr CO2 80-yr trend				5.9	5.5 (1.5, 8.1)	5.4 (3.3,6.7)	6.6 (1.1, 10.1)			
Knutson and Tuleya 2004 (Pressure fall) (ref 9)	GFDL Hurricane Model	9 km grid inner nest; Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				13.8	13.0 (3.2, 21.6)	13.6 (8.0, 16.5)	14.8 (3.6, 25.0)			
Knutson et al. 2001 (ref 61)	GFDL Hurricane Model	18 km grid w./ ocean coupling	GFDL R30 downscale, +1%/yr CO2 yr 71-120 avg	6									
Knutson et al. 2008 (ref 22)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100					2.9					
Oouchi et al. 2006 (ref 10) (Average intensity)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	10.7	8.5	14.1		11.2	4.2	0.6	-12.8	17.3	-2.0
Oouchi et al. 2006 (ref 10) (Average annual maximum intensity)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	13.7	15.5	6.9		20.1	-2.0	-5.0	-16.7	8.2	-22.5
Semmler et al. 2008 (ref 58)	Rossby Centre regional model	28 km	16 yr control and A2, 2085-2100					+4					
Walsh et al. 2004 (ref 59)	CSIRO DARLAM regional model	30 km	3xCO2; 2061-2090 minus 1961-1990										+26% P<970 mb
Bengtsson et al. 2007 (ref 23)	ECHAM5 timeslice	T319 (~40 km)	2071-2100, A1B		+42%, #>50 m/s								
Chauvin et al. 2006 (ref 11)	ARPEGE Climat Timeslice	~50 km	Downscale - CNRM B2 - Hadley A2					~0 ~0					
Stowasser et al. 2007 (ref 56)	IPRC Regional	~50 km	Downscale NCAR CCSM2, 6xCO2						PDI : +50%				
Leslie et al. 2007 (ref 57)	OU-CGCM with high-res. window	Up to 50 km	2000 to 2050 control and IS92a (6 members)										+100 % #>30 m/s

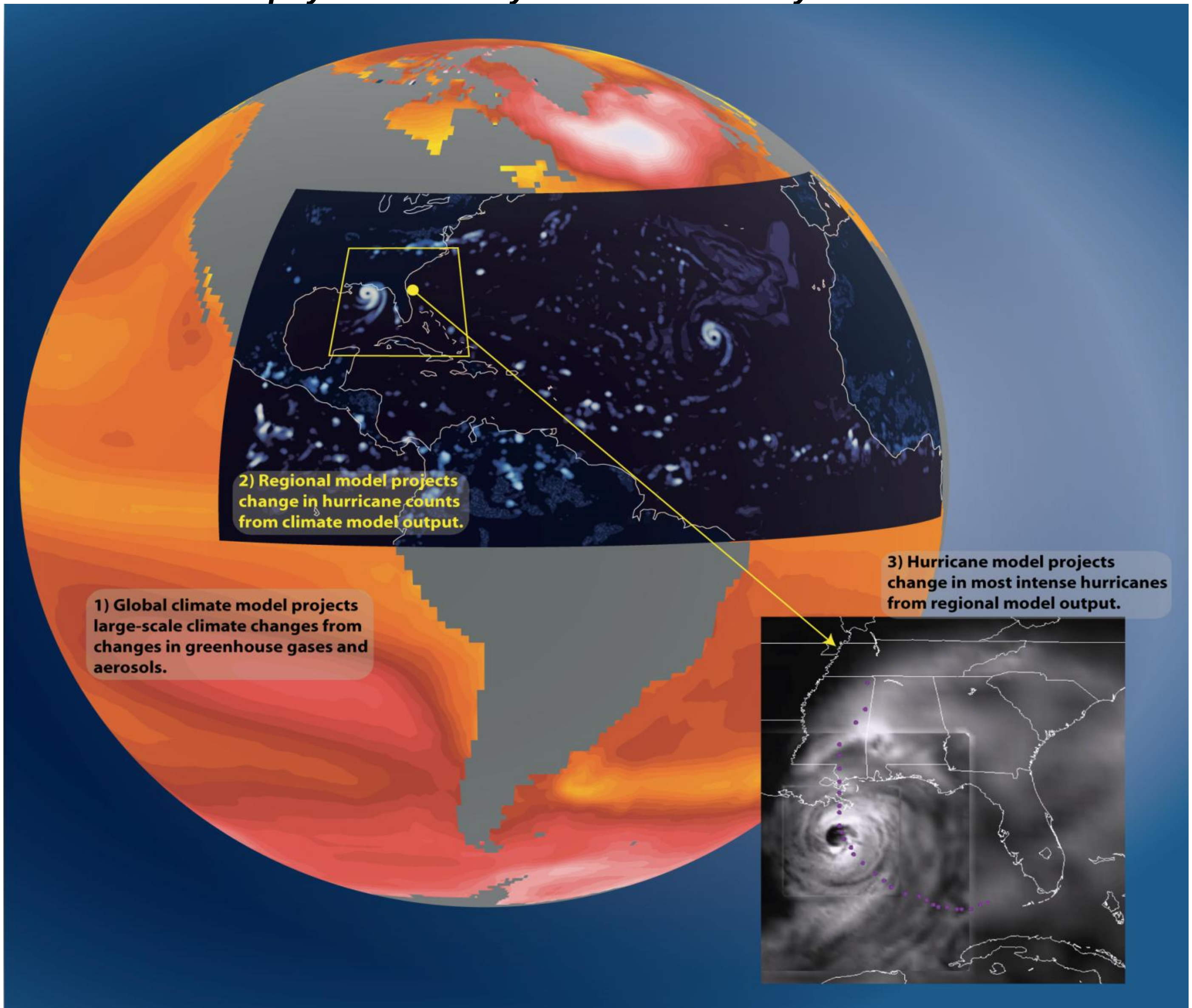
Blue = decrease

Red = increase

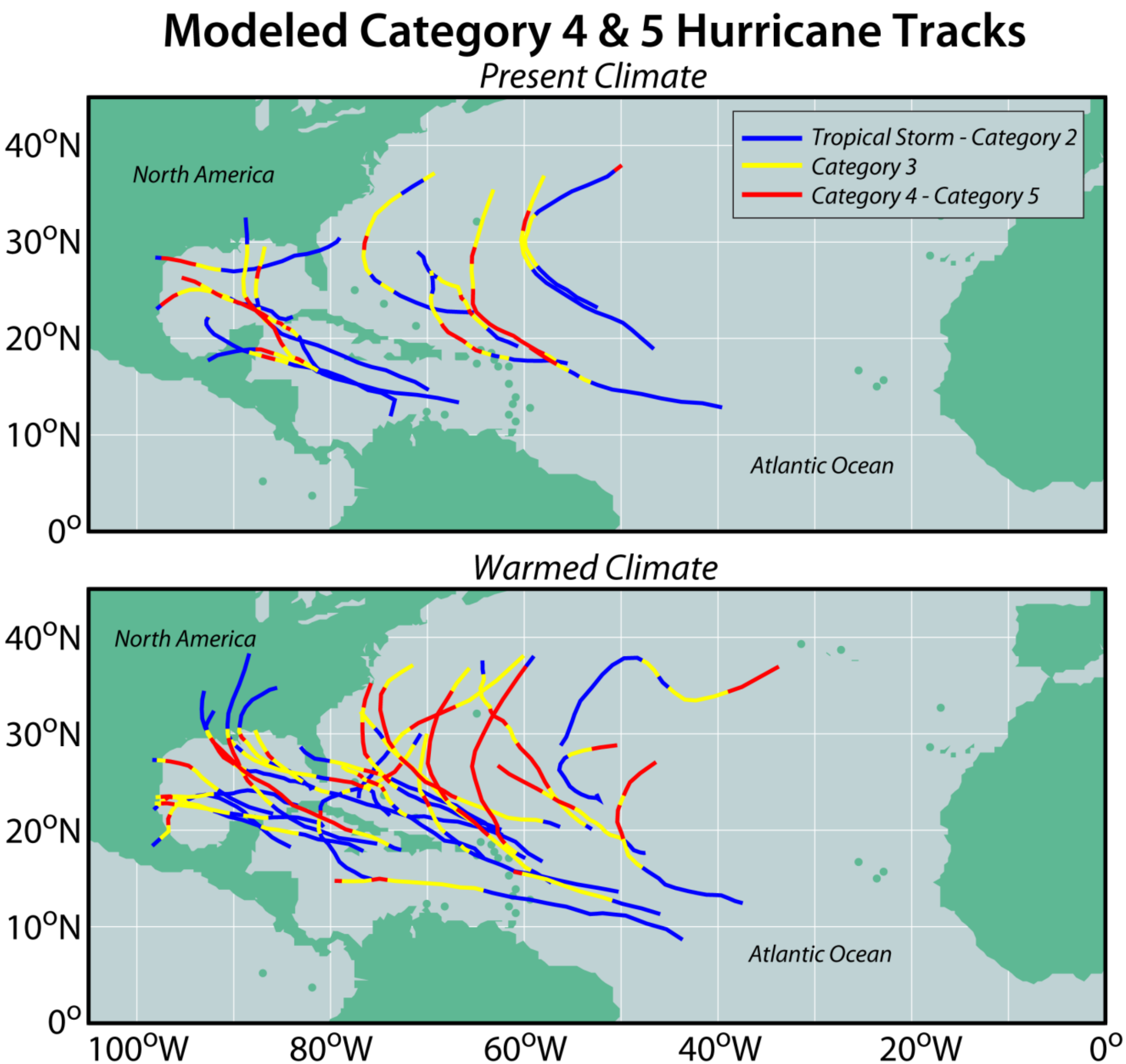
Source: Knutson et al., Nature Geoscience 2010.

Example of a "double-downscaling" method used to explore frequencies and intensities of Atlantic hurricanes at high resolution

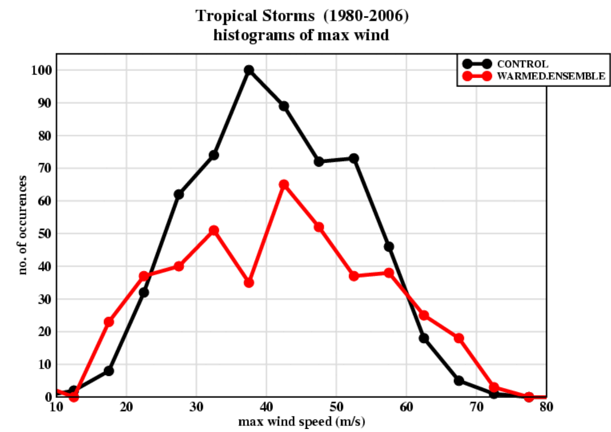
Geophysical Fluid Dynamics Laboratory/NOAA

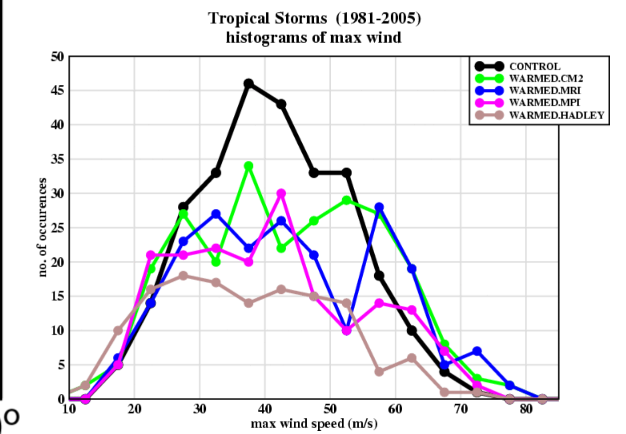


Late 21st Century Climate Warming Projection-- Average of 18 CMIP3 Models



The Cat 4-5 increase is not projected for all of the 18 individual models:

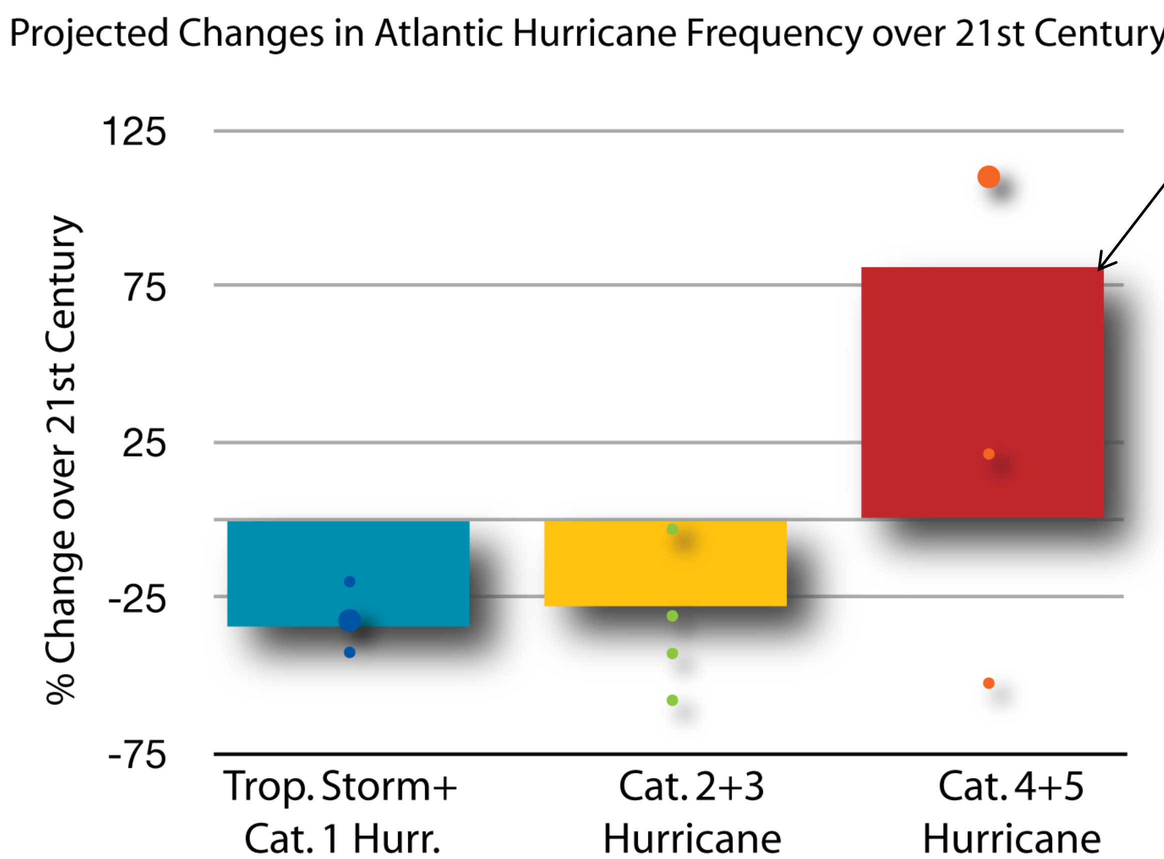




(27 Simulated Hurricane Seasons)

Source: Bender et al., Science, 2010

SUMMARY OF PROJECTED CHANGE



Cat 4+5 frequency: 81% increase, or 10% per decade

Estimated net impact of these changes on damage potential: +28%

• Colored bars show changes for the18 model CMIP3 ensemble (27 seasons); dots show range of changes across 4 individual CMIP models (13 seasons).

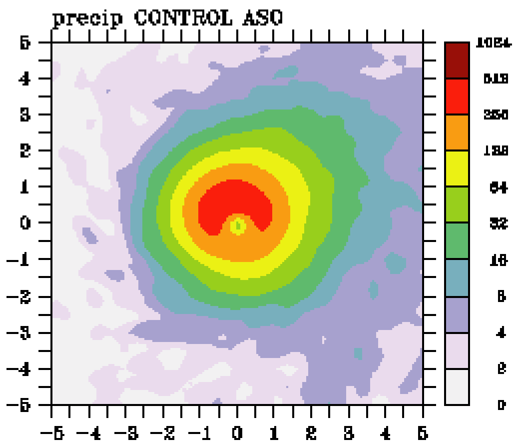
Source: Bender et al., *Science,* 2010.

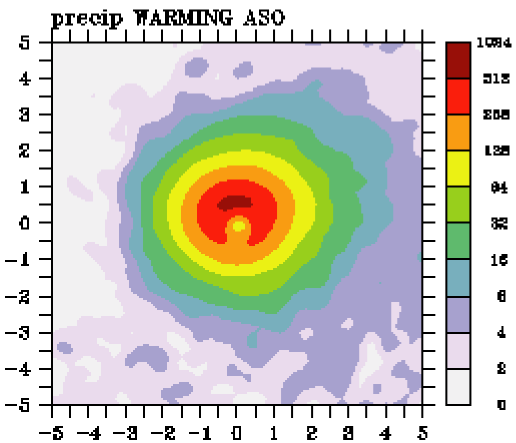
Tropical Cyclone Precipitation Rate Projections (Late 21st Century)

Blue = decrease; Red = increase

Table S3. TC Precipitation Projections

Reference	Model/type	Resolution/	Experiment	Basins	Radius around storm center	Percent Change
Hasegawa and Emori 2005 (ref 54)	CCSR/NIES/FRC GC timeslice	T106 L56 (~120km)	5x20y at 1xCO2 7x20y at 2xCO2	NW Pacific	1000 km	+8.4
Yoshimura et al. 2006 (ref 55)	JMA GSM8911 Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	Global	300 km	+10 (Arakawa-Schubert) ~ +15 (Kuo)
Chauvin et al. 2006 (ref 11)	ARPEGE Climat Timeslice	~50 km	Downscale CNRM B2 Downscale Hadley A2	Atlantic	n/a	Substantial increase
Bengtsson et al. 2007 (ref 23)	ECHAM5 timeslice	T213 (~60 km)	2071-2100, A1B	Northern Hemisphere	550 km Accum. Along path	+21 (all TCs) +30 (TC > 33 m/s)
Knutson et al. 2008 (ref 22)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100	Atlantic	50 km 100 km 400 km	+37 +23 +10
Knutson and Tuleya 2008 (ref 62)	GFDL Hurricane Model (idealized)	9 km inner nest	CMIP2+ +1%/yr CO2 80-yr trend	Atlantic, NE Pacific, NW Pacific	~100 km	+22
Gualdi et al. 2008 (ref 34)	SINTEX-G coupled model	T106 (~120 km)	30 yr 1xCO2, 2xCO2, 4xCO2	Global	100 km 400 km	+6.1 +2.8





Knutson et al. (2008)
Avg. Rainfall Rate Increases:
- 50 km radius: +37%
- 100 km radius: +23%
- 150 km radius: +17%
- 400 km radius: +10%

Average Warming: 1.72°C

SUMMARY ASSESSMENT (other storm characteristics/impacts):

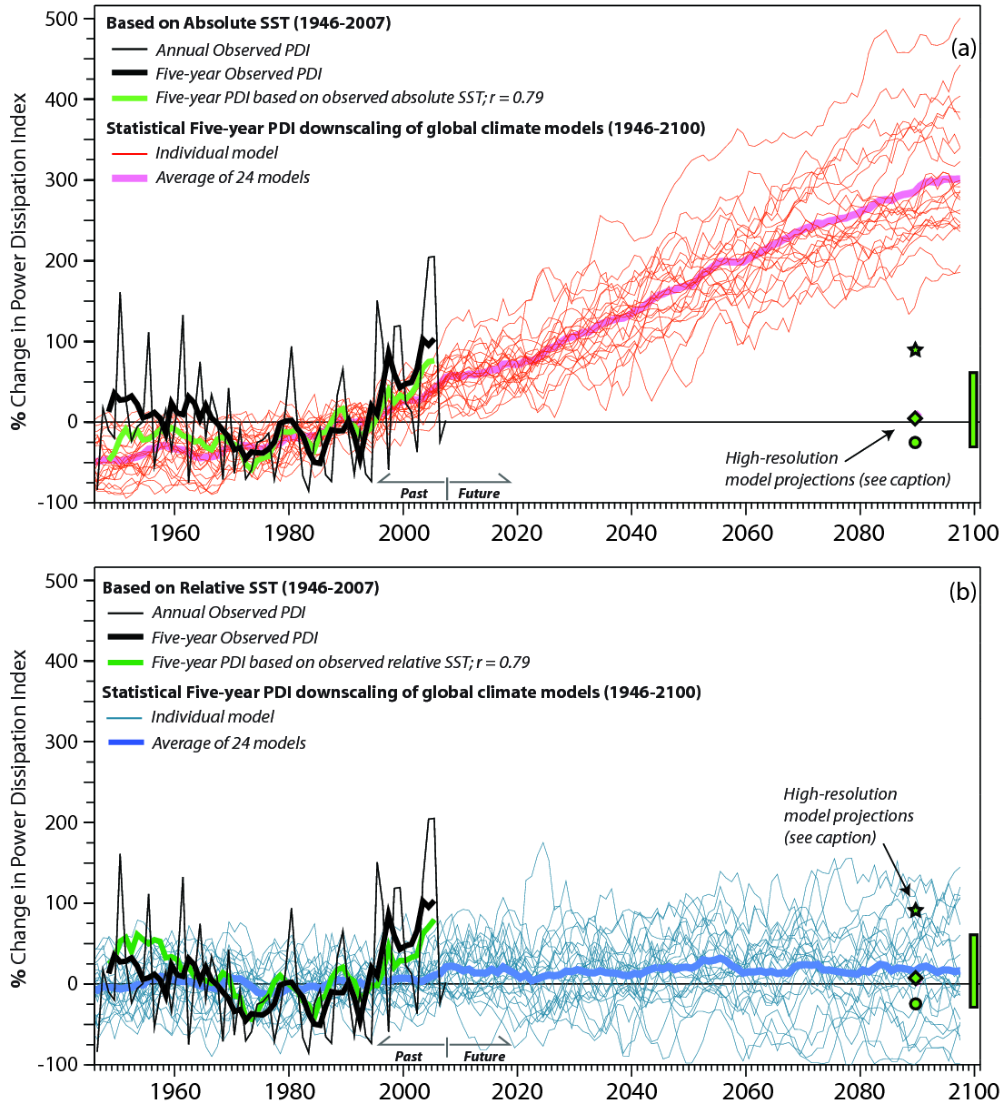
Tropical Cyclone Projections: Genesis, Tracks, and Duration

We have low confidence in projected changes in genesis location, tracks, duration, or areas of impact. Existing model projections do not show dramatic large-scale changes in these features.

‘Possible Range’ of Projections?

Or, speculations on what could make things worse than projected?

Atlantic Hurricane Acitivity vs. Sea Surface Temperature



A significant statistical correlation exists between Atlantic TC power dissipation and SST since 1950 (top).

A comparable correlation exists between the power dissipation and the tropical Atlantic SST relative to mean tropical SST (bottom).

These two statistical relations lead to dramatically different ‘projections’ of late 21st century Atlantic TC activity, ranging from a dramatic ~300% increase to little change. The large (~300%) increase scenario is not supported by existing downscaling models (symbols).

‘Possible Range’ of Projections?

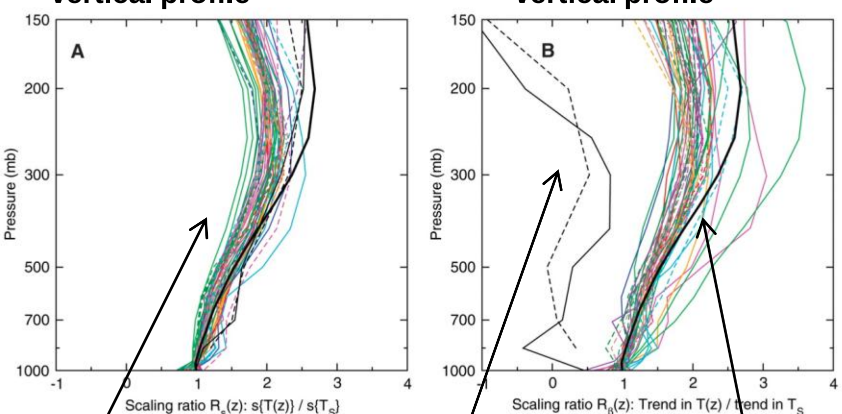
Or, speculations on what could make things worse than projected?

Vertical profile of tropospheric warming:

- **Models and theory predict that the vertical profile of tropical tropospheric warming will amplify with height, while radiosonde-based and some satellite-based observations suggest that the troposphere has warmed uniformly with height. A uniform warming with height would be ‘de-stabilizing’, and would imply future hurricane activity increases much larger than currently projected (by ~ 3-4x). Modeling studies and critical reanalysis of observations (e.g., using winds to infer temperature trends) suggest that the observed of ‘destabilization’ of tropical temperatures from radiosondes and satellites are likely unreliable.**

Interannual Variability vertical profile

Trend (1979-1999) vertical profile



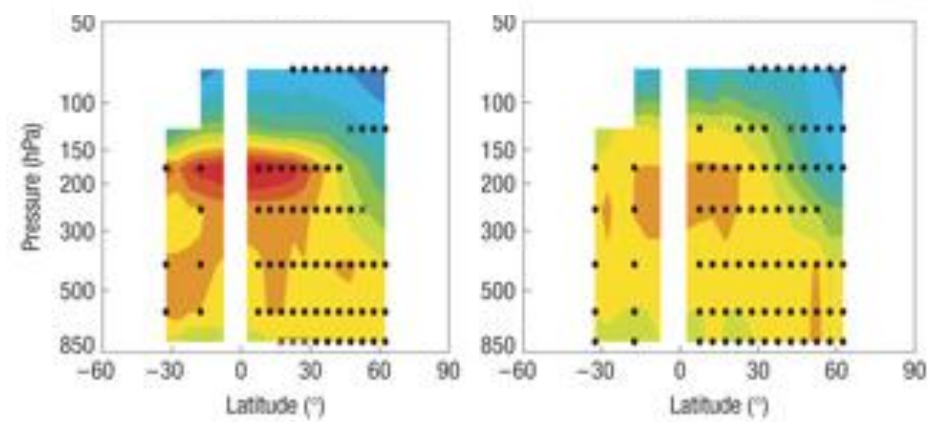
Radiosondes, models and theory

Radiosondes

Models and theory

Trend (1970-2005) derived from Radiosonde winds

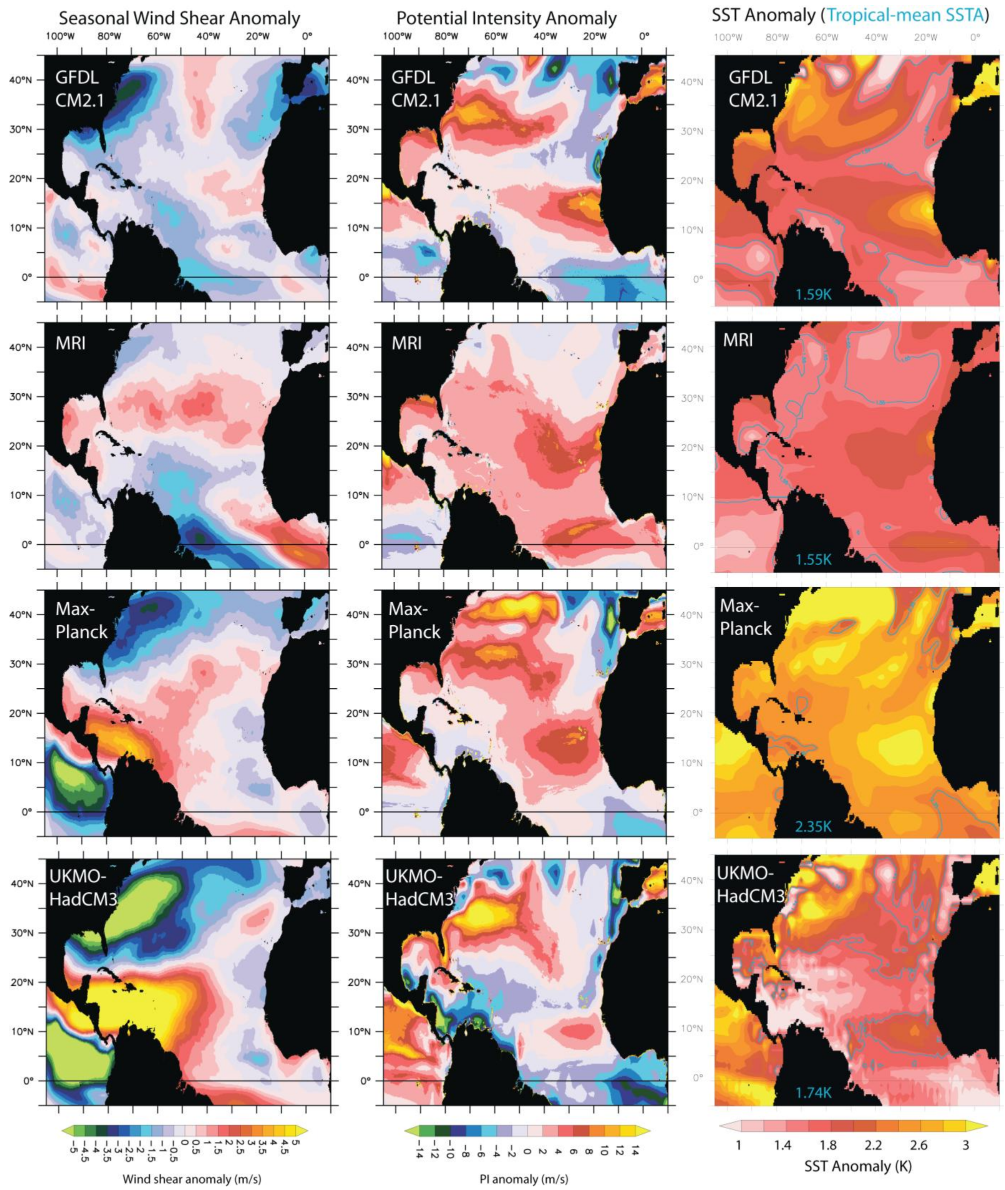
Trend (1970-2005) from climate models



Sources: Santer et al. 2005; Allen and Sherwood 2008

‘Possible Range’ of Projections?

Or, speculations on what could make things worse than projected?



The range of possible projections could be even broader than inferred from the AR4 models (sample of 4 models shown at left):

- **IPCC AR4 models favor a weak El Nino-like signature to the pattern of 21st century warming, and strongly favor enhanced vertical wind shear over the Caribbean and tropical Atlantic. However, some models project little change in wind shear and some researchers (Cane et al.) argue that the Pacific warming signal will be distinctly La Nina-like, which could substantially impact Atlantic hurricane projections.**

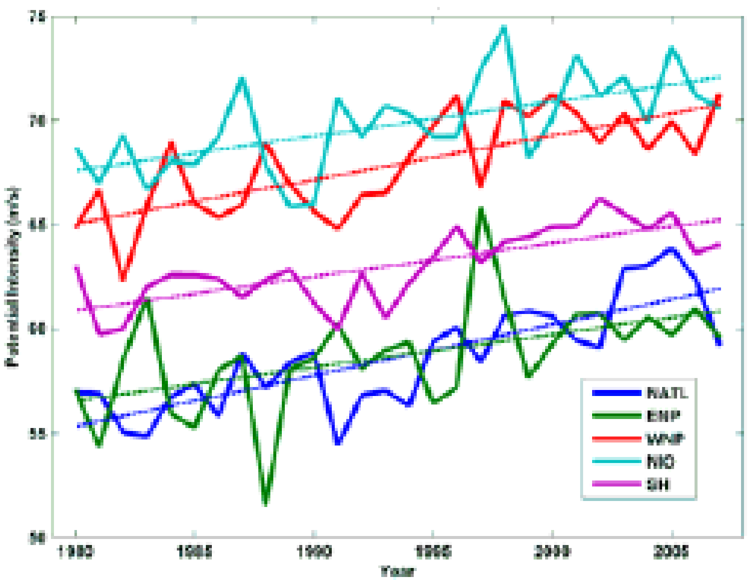
‘Possible Range’ of Projections?

Or, speculations on what could make things worse than projected?

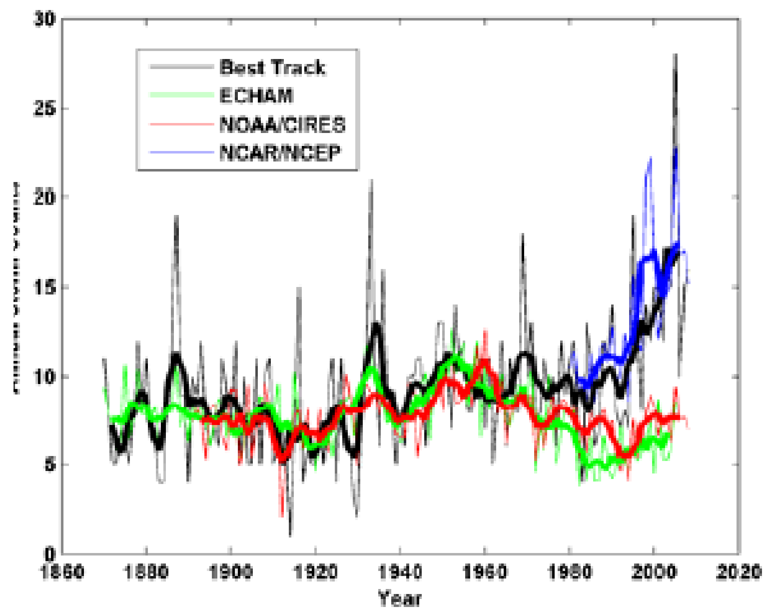
Lower stratospheric temperatures:

• Can lower stratospheric or tropopause transition layer (TTL) temperatures (apparently cooling) affect tropical storm frequency or hurricane intensity? Emanuel statistical/dynamical downscaling: yes for both. Current GFDL dynamical models: no for tropical storm frequency, not clear for intensity (upper tropospheric temperatures affect hurricane intensity in the GFDL models). Also, are NCEP potential intensity trends since 1980 reliable or do they suffer from inhomogeneity problems?

Potential Intensity trends since 1980 from NCEP Reanalysis



Statistical/Dynamical Downscaling of Atlantic Tropical Storm Frequency (1870-2005)



Source: K. Emanuel, AMS Hurricanes and Tropical Meteorology Conference abstract, 2010.

‘Possible Range’ of Projections?

Or, speculations on what could make things worse than projected?

Tropical cyclone-induced changes in ocean heat transport:

- **Possible role of tropical cyclones in ‘equable’ climates of 3-5 million years ago being investigated, but implications for this mechanism on climate for next century or so remain highly speculative. Tropical cyclones cause less than 10% of global poleward heat transport in the current climate, according to the latest studies.**

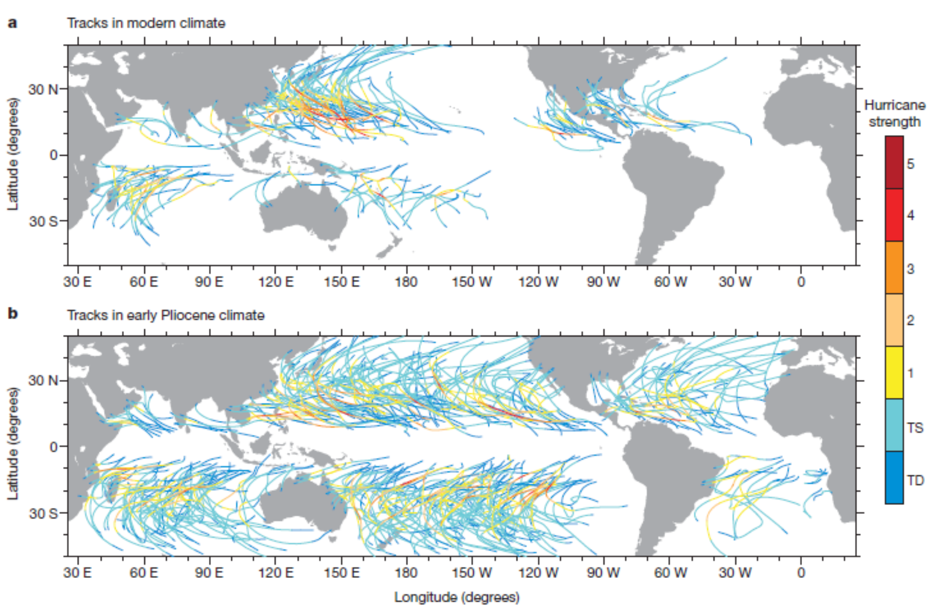


Figure 2 | The tracks of tropical cyclones simulated by the SDSM. a, In the modern climate, and b, in the early Pliocene climate. The colours indicate hurricane strength—from tropical depression (TD; blue) to tropical storm (TS; cyan) to category-5 hurricanes (red). The tracks shown in each p a two-year subsample of 10,000 simulated tropical cyclones.

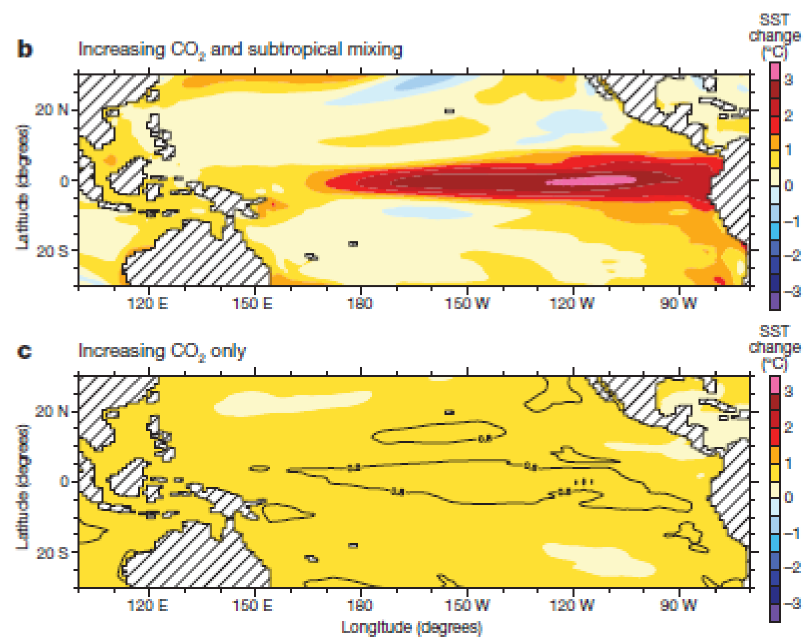


Figure 4 | SST changes in the tropical Pacific simulated by the coupled

Overview of Assessments

Climate Change Detection and Attribution:

- It remains uncertain whether past changes in tropical cyclone activity exceed natural variability levels.

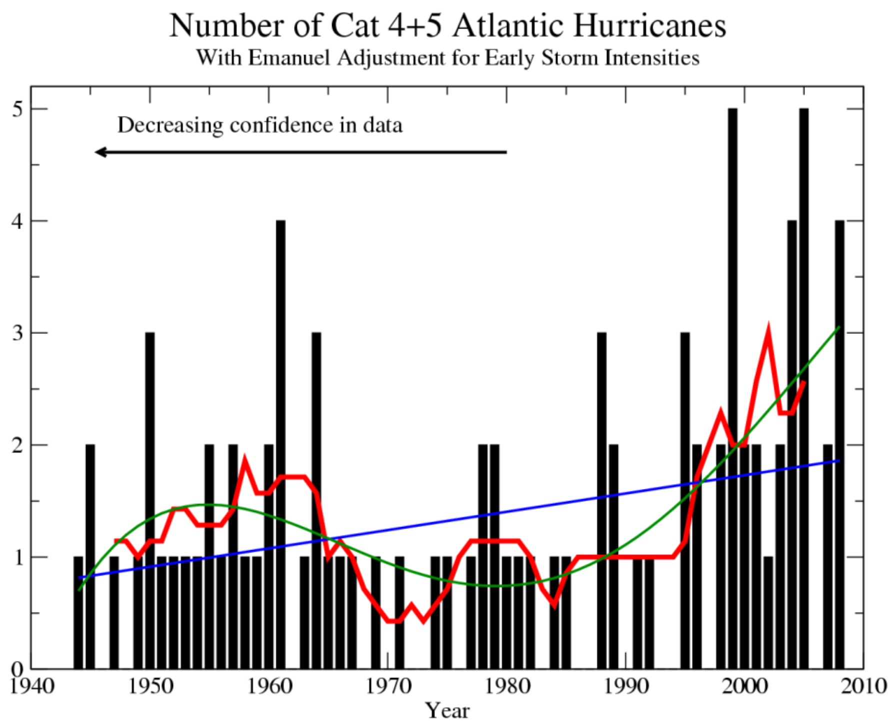
Projections for late 21st century:

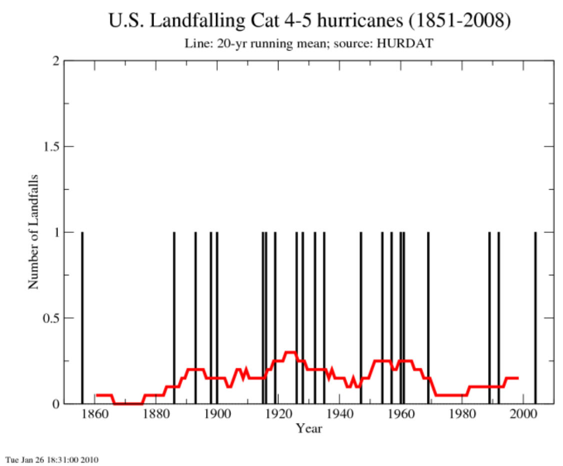
- Likely fewer tropical storms globally (~no change to -34%), with even greater uncertainty in individual basins (e.g., the Atlantic).
- Likely increase in average hurricane wind speeds globally (+2 to11%), though not necessarily in all basins
- More frequent very intense storms (> 50% chance these will increase by a substantial percentage in some basins).
- Likely higher rainfall rates in hurricanes (roughly +20% within 100 km of storm)
- Sea level rise is expected to exacerbate storm surge impacts even assuming storms themselves do not change.

Emergence Time Scale: If the observed Cat 4+5 data since 1944 represents the noise (e.g. through bootstrap resampling), how long would it take for a trend of ~10% per decade in Cat 4+5 frequency to emerge from noise?
Answer: **~60 yr** (by then 95% of cases are positive)

Instead, assume residuals from a 4th order polynomial: **55 yr**

Instead, resample chunks of length 3-7 yr: **65-70 yr**





Source: Bender et al., *Science*, 2010.

The Impact of Climate Change on Tropical Cyclone Damages

Robert Mendelsohn, Yale University
Kerry Emanuel, MIT
Shun Chonabayashi, Cornell University

Abstract

This paper constructs an integrated assessment model of tropical cyclones in order to quantify the additional damage that climate change might cause by 2100 around the world. The paper begins with the A1b SRES emission trajectory from the Intergovernmental Panel on Climate Change (IPCC). The trajectory approaches a stable concentration of greenhouse gases of about 720ppm by 2100. This emission trajectory is used in four general circulation climate models: CNRM, ECHAM, GFDL, and MIROC. The climate models are used to predict hurricanes in the 1980-2000 climate and the 2180-2200 climate. The models predict a range of future global temperature changes from 2.9°C to 4.5°C. The climate outcomes from these models are then fed into a regional climate model that is capable of predicting hurricane behavior in each ocean basin.

A tropical cyclone generator creates potential hurricanes randomly in each basin for both the current climate and the future climate. The model follows these storms across each ocean and determines which storms develop into hurricanes and which do not. A total of 17,000 tropical cyclones are generated in each of the 8 climate scenarios (current and future climate with each of 4 climate models). The model does a reasonable job of predicting the frequency, intensity, and location of the hurricane distribution observed in the current climate.

We detect the influence of climate change by comparing the results of current predicted hurricanes versus future predicted hurricanes. Except in the GFDL scenario which predicts a

doubling of hurricanes, the frequency of hurricanes is not predicted to change because of warming. However, in the western North Atlantic and the western North Pacific, hurricane intensity consistently increases in all four climate scenarios. In the other ocean basins, the change in hurricane intensity is inconsistent, sometimes increasing and sometimes decreasing across the climate scenarios. Whether climate change has an effect on hurricane intensity in the other basins is therefore highly uncertain.

This paper advances on the underlying science of hurricanes by examining the damages that hurricanes might cause. Beginning with observed hurricanes and observed levels of damages, the paper calculates a damage function of tropical cyclones. Using US data, the study calculate a relationship between storm damages and storm intensity. The analysis confirms earlier results suggesting a highly nonlinear relationship between storm intensity and storm damages. The study finds that the minimum pressure of a storm is a better predictor of damages than maximum wind speed (the measure used in the damage literature). Using international data, the study then examines the link between storm damages and the characteristics of the affected areas. The study finds that damages increase with both income and population density as expected. However, damages increase less than proportionally with both variables contrary to assumptions made by previous authors.

Current predicted tropical cyclone damages are then calculated using the current income and population density of each country and the distribution of tropical cyclones predicted in the current climate. Damages are calculated for each storm that is predicted to strike each country or come close enough to cause significant damage. The expected value of damages is adjusted to equal the observed damages in each country over the last 20 years. The global damages from tropical cyclones are currently $26 billion (0.043 percent of Gross World Product (GWP)).

The analysis then calculates what damages would occur if income and population density were to increase as projected by 2100. Given the projected growth rates for each country, damages are calculated again using the current distribution of tropical cyclones. Global damages are projected to double to $55 billion just because of the increase in income and population in each country. Damages increase faster in Asia because of the projected faster growth rate of income in that region. Tropical cyclones damages as a fraction of GWP are expected to fall by 2100 to 0.01 percent of GWP because damages increase less than proportionally with income.

The final step in the analysis is to compute the effect of climate change. The damages from the future economy with storms from the current climate are compared to the damages from the future economy with storms from the future climate. Warming doubles the global damage caused by tropical cyclones. Warming causes an additional $54 billion of damage per year (0.01 percent of GWP). Looking across the different climate models, warming increases damages between $28 and $68 billion/yr.

The effects are not uniformly felt across the world. The increase in storm intensity in the North Atlantic and North Pacific lead to substantial damages in the northeastern edge of the Western Hemisphere and in the eastern edge of Asia. The United States, China, and Japan account for 88 percent of the expected global damages. The countries with the biggest damages as a percent of GDP are predominantly small islands in the Caribbean.

Warming also changes the distribution of damages. With current climate, the top 10% worst storms (measured by damage) cause 90% of the total damage and the top 1% worst storms cause 58% of the damage. With the future climate, the top 10% worst storms cause 93% of the damage and the top 1% of storms cause 64% of all the damage.

Further work is required to fully understand how to adapt to tropical cyclones. There are three mechanisms that cause damage: storm surge, high winds, and flash flooding. Further research is needed to predict the consequences of each of these mechanisms and how different adaptation strategies might change the distribution of damages. The fact that so much of the damages are concentrated in rare (once in a century or millennium) but very powerful events makes adaptation difficult.

Capsule

Climate science and economics are combined to estimate the future tropical cyclone damages from economic growth and from climate change.

Main Text

I. Introduction

Tropical cyclones (hurricanes, typhoons) have become an icon of climate change. Scientists report an increase in tropical cyclone intensity over the last 30 years[1,2] and a dramatic increase in tropical cyclone damages over time[3,4]. And yet despite these findings, the link between climate change and tropical cyclone damage remains controversial. Tropical cyclones are rare events and appear to be subject to long term variability so it is difficult to detect changes in underlying frequencies and severity[5]. The people and assets in harm's way is also increasing over time, which may explain the trend in tropical cyclone damage[6,7,8]. The historic record may simply not be long enough and clear enough to detect how climate may be affecting tropical cyclones.

The average current global damage from tropical cyclones is $26 billion per year[9]. A tropical cyclone model predicts there will be an increase in tropical cyclone intensity in the Atlantic Ocean[10]. Using this average change in intensity, several authors predict that damage will double[11,12,13] .

This paper takes a different approach that captures the full range and distribution of tropical cyclones to estimate the impact of climate change on the damages caused by tropical cyclones. The paper relies on an integrated assessment that combines the insights of a hurricane generator with the consequences of a damage model. Beginning with an emissions trajectory, four climate models predict future climate scenarios. A tropical cyclone generator is then used to seed potential storms in each ocean basin[10]. The storms are then permitted to develop given the conditions predicted by each climate model. A total of 17,000 storms are generated with and without climate change. The model is able to capture the different outcomes in each ocean basin and measure how storm intensity and location changes. For each storm, a damage model is then used to predict the damages upon landfall.

The analysis begins by forecasting how current baseline damages from tropical cyclones would change because of future increases in what is in harm's way. From this future baseline, we then evaluate the effects of climate change. We predict how the change in tropical cyclones generated by the current versus future climate affect damages. The analysis captures changes in the frequency of storms, the landfall of storms, and the intensity of storms. The analysis carefully controls for what is in harm's way before estimating the impact of climate change. The results provide the first geographically detailed estimates of how storm damages change around the world.

The next section of the paper describes the methodology in more detail. The empirical findings of the paper are then reviewed in Section III. The paper concludes with a review of the major findings and some policy observations.

II. Theoretical Methodology

The economic damage (*D*) from each tropical cyclone is the sum of all the losses caused by it. In this analysis, we focus on economic damages primarily from lost buildings and infrastructure. In order to model tropical cyclones, it is critical to recognize that they are rare events and depend on the frequency or probability (π) of each storm in each place. The characteristics (*X*) of each storm are also important. Damages also depend upon where the tropical cyclone strikes (*i*). Atmospheric science can help predict the probability a tropical cyclone (*j*) with particular characteristics (*X*) will strike each place (*i*) given the climate (*C*):

$$\pi_{ij} = \pi(X_{ij}, C) \tag{1}$$

The actual damage associated with any given tropical cyclone (*j*) also depends on the vulnerability (*Z*) of each place (*i*):

$$D_i = D(X_i, Z_i) \tag{2}$$

The expected value of tropical cyclone damages is:

$$E[D] = \sum_j \sum_i \pi(X_{ij}, C) D(X_i, Z_i) \tag{3}$$

Because the damage function is highly nonlinear, the expected damage is the sum of the damages caused by every storm. It is very important to model the entire distribution of damages in order to capture the true effect of tropical cyclones.

The damage caused by moving from the current climate C0 to a future climate C1 is the change in the expected value of the damages:

$$W = E[D(C1)] - E[D(C0)] \qquad (4)$$

For any given time period, climate change could change damages because the frequency, intensity, or the location of storms change. In this study, we compute tropical cyclone damages in each country of the world and then aggregate the results to larger regions. Country specific results are reported in Appendix A.

Equation 4 calculates the expected welfare loss from climate change. We also calculate the return rate for storms causing each level of damage. This is a relationship between the average years between tropical cyclones that cause specific amounts of damage:

$$return = 1 / prob(D) = g(D(X)) \qquad (5)$$

Policy makers may be interested in the return rate because it provides information about the distribution of damages. Insurers would also be interested in the return rate because it provides information about how much catastrophic insurance to buy.

III. Methodology

The integrated assessment predicts tropical cyclone damages given different climates. The analysis relies on the A1B SRES emission scenario generated by the Intergovernmental Panel on Climate Change[14]. The emission scenario assumes that mitigation is tightened gradually over time so that greenhouse gas concentrations finally peak and stabilize at 720 ppm.

We rely on four climate models: CNRM[15], ECHAM[16], GFDL[17], and MIROC[18]. Each climate model predicts both the current climate and the climate in 2100. CNRM predicts a global warming of 2.9°C, ECHAM predicts 3.4°C, GFDL predicts 2.7°C, and MIROC predicts 4.5°C. These changes in climate raise sea surface temperatures which in turn fuel the tropical cyclones. However, there are other changes such as wind shear and humidity that can affect tropical cyclone intensity. In addition, changing atmospheric winds can alter the tracks of tropical cyclones.

Using a tropical cyclone generator in each ocean basin, the climate data is used to project tropical cyclone tracks[10]. A total of 17,000 tropical cyclone tracks are generated across the five oceans with and without climate change for each climate model (8 sets of 17,000 tropical cyclones). For each track, we follow where the tropical cyclone makes landfall or passes close enough to land to create damage. The minimum barometric pressure and the maximum wind speed at landfall of each storm are recorded. The hurricane generator also predicts the expected frequency of tropical cyclones in each ocean basin.

Figure 1 presents a sample of the tracks generated in each ocean basin. The figure reveals that there is a zone just north and south of the equator where the storms are the most intense. As storms veer off to middle and high latitudes, they tend to lose power.

Figure 2 shows the changes in power by ocean basin attributable to climate change. Power consistently climbs in the North Atlantic and the North Western Pacific ocean basins across all four climate models. These predicted changes in tropical cyclone power will especially influence damages in North America and eastern Asia respectively. Changes in the other ocean basins are not consistent across the climate models.

A damage function is then estimated to predict the damages that each storm will cause. The coefficient for storm intensity was estimated using aggregate damages per storm and storm characteristics at landfall from US storms since 1960[19]. This historic data was matched with coastal population density and income[20] near landfall. The log-log regressions in Table 1 reveal the elasticities of each variable with respect to damage. The first two columns using US data reveal that damages are a highly nonlinear function of wind speed and minimum barometric pressure. The regressions also reveal that minimum pressure provides more accurate estimates of damages than maximum wind speed. It is likely that minimum pressure is a better predictor of storm intensity because it is difficult to measure maximum wind speed accurately. The literature relies solely on wind speed to measure damages[11,12,13,21].

The third column of Table 1 presents a damage regression using international data[9]. Damages increase with income but fall with population density. The elasticities of these variables are significantly less than 1 (contrary to assumptions in the literature[6,8,11,12]). Storm damages consequently do not rise proportionally with income or population.

Given the empirical results above, the preferred damage function has the following form:

$$D = A_D * MP^{-86} Y^{0.06} Pop^{-0.2} \tag{6}$$

The expected damages for each country were calculated by summing the product of the probability of each storm times the damage it causes for each country. Storm damages are truncated so that they cannot exceed the complete destruction of all the capital in the five counties near landfall. The parameter A_D is calibrated for each country so that the damage from the current predicted set of storms striking each country equal the observed damage in recent history.

IV. Results

The annual observed global damage from tropical cyclones is $26 billion (0.043 percent of GWP)[9]. Our first task is to project how these damages would increase with future economic growth, holding climate constant. Both population and income are projected to 2100. The population in each country is assumed to follow projections that lead to a global population of 9 billion[22]. GDP is assumed to grow an annual rate of 2 percent in developed countries, 2.7 percent in developing countries, and 3.3 percent in emerging countries. Dividing GDP by population yields a future prediction of income per capita for each country in 2100. The damages from the set of storms given current climate are then recalculated using the damage function and future levels of population density and income. With future baseline conditions in 2100, the global expected damage more than doubles to $55 billion per year (0.01 percent of GWP). Damage grows more slowly than GDP because the coefficients on income and population in the damage function are less than 1.

In order to calculate the impact of climate change, a new set of tropical cyclones is generated given the 2100 climate predicted by each of the climate models. The impact of climate change is the difference in damages caused by the new set of cyclones versus the original set of cyclones. Both measures of damage use future economic conditions. By evaluating the impact of climate change using future conditions rather than current conditions, the impacts are larger because more is in harm's way in the future. Damages are computed from all 17,000 storms before and after climate changes.

The results reveal that climate change by 2100 is expected to cause tropical cyclone damages to increase $54 billion/yr (a 100% increase above the future baseline). This additional damage is equal to 0.01 percent of GWP. Looking across the different climate models, damages rise between $28 and $68 billion/yr. These aggregate global results are very consistent with most of the findings in the literature that climate change would double tropical cyclone damages.

However, the new results reveal that the distribution of damages is not even across the world. Figure 3 displays the damages caused by climate change in each continent. Asia and North America are the two continents that are consistently predicted to be damaged by warming across all four climate models. The increased intensity of North Atlantic and Western Pacific storms are causing these effects. The additional damage in North America is equal to $30 billion/yr and the additional damage in Asia is equal to $21 billion. The additional storm damage in the rest of the world is just $3 billion. For some regions and models, the damages from tropical storms actually fall with warming.

Figure 4 displays climate change tropical cyclone damages as a fraction of GDP in 2100. The figure illustrates how burdensome the change in tropical storm damage will be to the economies in each region. The global average damage per unit of GDP is 0.01 percent. North America (0.03 percent of GDP) and Asia (0.01 percent of GDP) have the largest additional impacts per unit of GDP. The tropical cyclone damages per unit of GDP caused by climate change are low in the remaining continents.

The continental averages, however, hide disproportionate effects in individual countries. Damages to all affected countries and each model are shown in Appendix A. The countries with the largest average impacts from climate change are the United States ($30 billion), Japan ($9 billion), and China ($8 billion). The damages from these three countries account for 88 percent of the global damages. The impacts are above 0.2 percent of GDP only in Antigua-Barbados, Cayman Islands, Dominica, Grenada, Honduras, Montserrat, St. Kitts-Nevis, Turks-Caicos, and the US Virgin islands. All but Honduras is an island in the Caribbean.

Although expected damages reveal long term damages, they hide changes in the distribution of damages. Figure 5 displays the relationship between damage and return rates for the GFDL climate scenario. The results for the other climate scenarios are similar. The figure reveals that common small storms are not different before and after climate change. Climate change increases the intensity of large storms. With the nonlinear damage function, this increased intensity translates into a significant increase in damages. The return period for the most powerful storms becomes shorter.

A surprisingly large fraction of the expected damages of tropical cyclones is caused by the most harmful storms. With current climate, the top 10% worst storms (measured by damage) cause 90% of the total damage. The top 1% worst storms cause 58% of the damage. With the future climate, the top 10% worst storms cause 93% of the damage and the top 1% of storms cause 64% of all the damage.

V. Conclusion

This study constructs an integrated assessment model to predict the tropical cyclone damages caused by climate change. The paper relies on a tropical cyclone generator and four climate models to predict thousands of tropical cyclones with and without climate change. The results indicate that tropical cyclone intensity will consistently increase in both the North Atlantic and North West Pacific ocean basins but not in the other ocean basins. The study then estimates a damage function associated with tropical storms from United States and international data. The analysis suggests that minimum pressure provides a more accurate measure of storm intensity than maximum wind speed and that damages are a highly nonlinear function of storm intensity. The results also suggest that damages increase with income but less than proportionally.

Increasing future income and population is predicted to increase annual tropical cyclone damages from $26 billion to $55 billion even with the current climate. However, damages as a fraction of GWP are expected to fall from their current rate of 0.04 percent in 2010 to 0.01 percent in 2100.

The impact of climate change is expected to double the damages from tropical cyclones by 2100 by $54 billion. This is equal to 0.01 percent of GWP. The estimated impact of climate change ranges from $28 to $68 billion depending on the climate model. The findings confirm the rough results of earlier tropical cyclone studies that relied on cruder methods.

The damages, however, are not evenly spread across the planet. Because tropical cyclones in the North Atlantic and North West Pacific Oceans consistently increase in intensity with warming, North America and eastern Asia have the largest and most consistent impacts. The average impact in Asia is an additional damage of $21 billion and the average impact in North America is an additional damage of $30 billion. Damages to the United States, Japan and China account for 88% of global damage. Climate change causes small damages in the rest of the world because the remaining continents see both small harmful and beneficial impacts depending on the climate model. Even controlling for GDP, North America and eastern Asia bear the highest damages per unit of GDP. However, the most vulnerable countries are relatively small Caribbean islands.

The results reveal that the damages from tropical cyclones are quite skewed. Even with the current climate, the 10 percent worst storms (measured by damage) account for 90 percent of the total damage. With warming, these powerful storms get even more harmful and the 10 percent worst storms account for 93 percent of the total damages. These especially large storms explain most of the damages caused by climate change and yet they occur very rarely. It may well take several centuries of observations to see whether the changes predicted in this paper actually have occurred.

There are many uncertainties associated with the forecasts made in this study. The emission path of greenhouse gases is highly uncertain because it depends upon the long term growth of the economy, the long term relationship between GDP and energy, and mitigation policies that may be adopted over the next century. The relationship between climate change and greenhouse gas concentrations is also quite uncertain as revealed by the results from the four climate models. Exactly how tropical cyclones will react to climate change is also uncertain as it depends upon many factors that are difficult to predict. The magnitude of the damages that future tropical storms will cause is uncertain. The damages with respect to storm intensity are very sensitive to minimum pressure and to the elasticity of population and especially income. Better international records of storm tracks and intensities and storm damages would help increase the accuracy of these estimates. How damages might change if there is both a change in tropical cyclones and sea level rise is uncertain (although they may be just additive[23]).

Finally, how society will adapt to tropical cyclones in the future is not yet clear. Currently, many countries have mal-adaptation policies that make matters worse by encouraging assets to remain or be placed in harm's way. For example, subsidizing flood insurance and capping the cost of catastrophe insurance makes it cheaper to live in risky locations. Even providing emergency disaster relief reduces the overall cost of developing a risky location. Reducing the implicit subsidies in these policies and actively discouraging development in risky locations could reduce damages significantly. In contrast, physical protection strategies such as building sea walls may be ineffective as protection against tropical cyclones. Most of the damage is caused by rare but very powerful storms. Walls would have to be very high to prevent inundation. These would be hard to justify if powerful storms are very infrequent at each location (once in a thousand years). Developing effective adaptation strategies to tropical cyclones is an important policy and research topic.

Acknowledgement

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Figure and Table Captions

Table 1: Regressions of Tropical Cyclone Damages

Figure 1: Storm tracks by minimum pressure (mb)

Figure 2: Change in Tropical Storm Power by Ocean Caused by Climate Change

Figure 3: Climate Change Impacts on Tropical Cyclone Damages by Region by 2100

Figure 4: Tropical cyclone damage in 2100 as a fraction of GDP

Figure 5: Return period in 2100 by US damage for ECHAM

Table 1: Regressions of Tropical Cyclone Damages

	US	US	International
Constant	12.19 (1.42)	607.5 (10.39)	15.17 (22.77)
Log (Wind Speed)	4.95 (7.83)	…	…
Log(Minimum Pressure)	….	-86.3 (9.96)	….
Log(income)	0.903 (0.96)	0.370 (0.45)	0.415 (6.44)
Log(Population Density)	0.458 (1.28)	0.488 (1.53)	-0.210 (3.04)
Adj Rsq	0.371	0.501	0.158
F Statistic	22.61	35.76	103.2
Observations	111	111	807

Note: T-statistics in parentheses. The functional form of the regression is log log. Source of US data is NOAA 2009 and the source of the international data is EMDAT 2009.

Figure 1 Storm tracks by minimum pressure (mb)

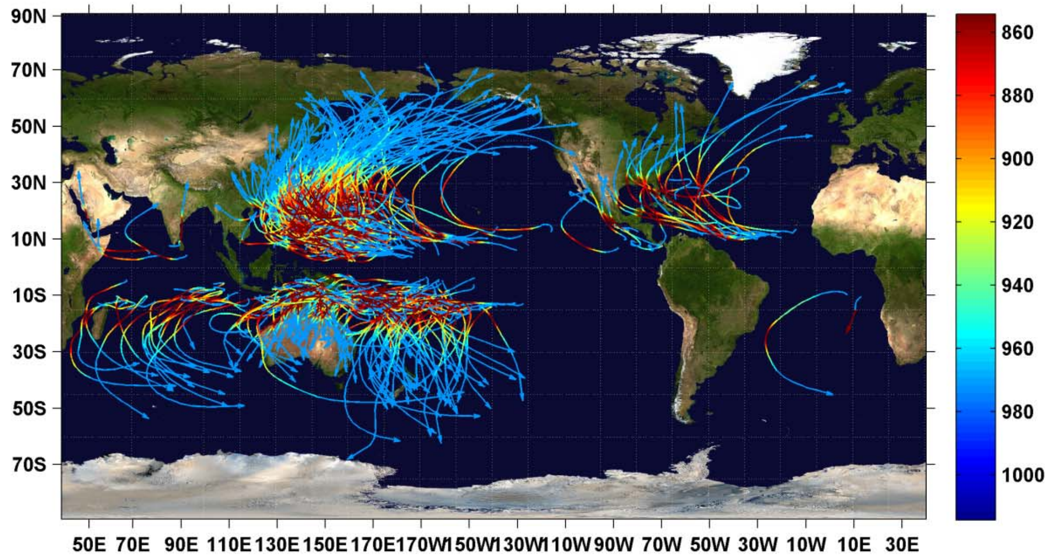
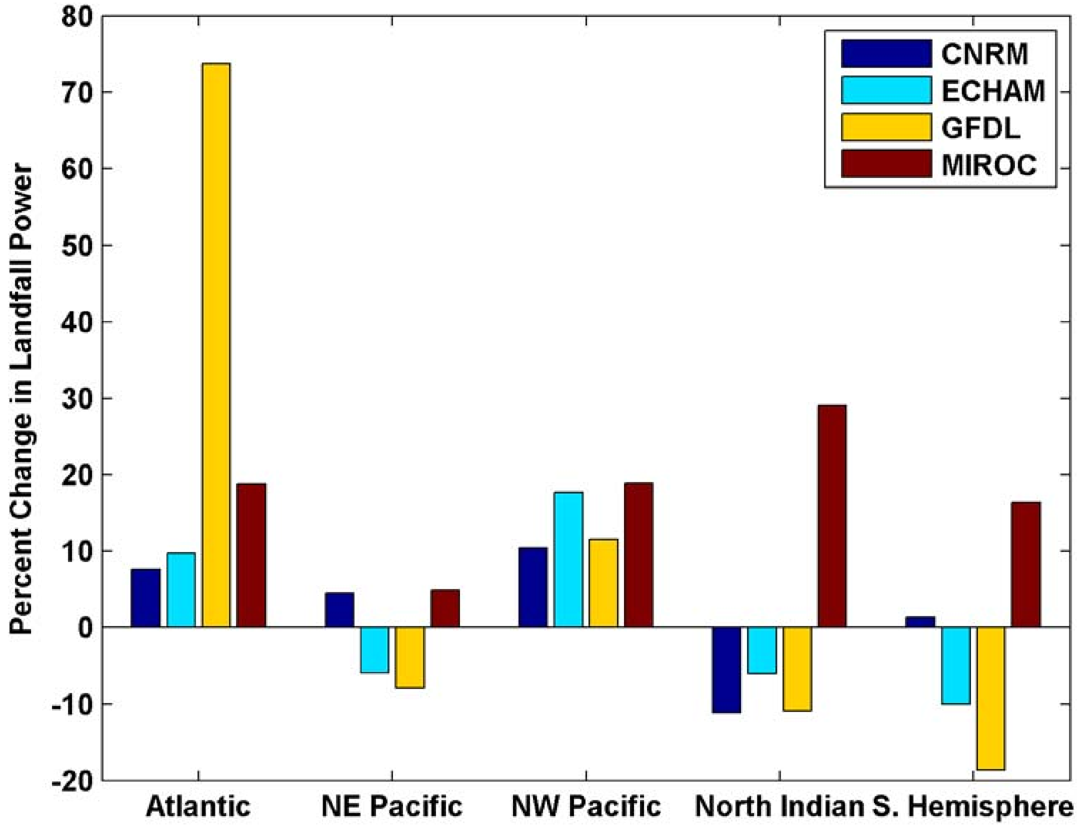
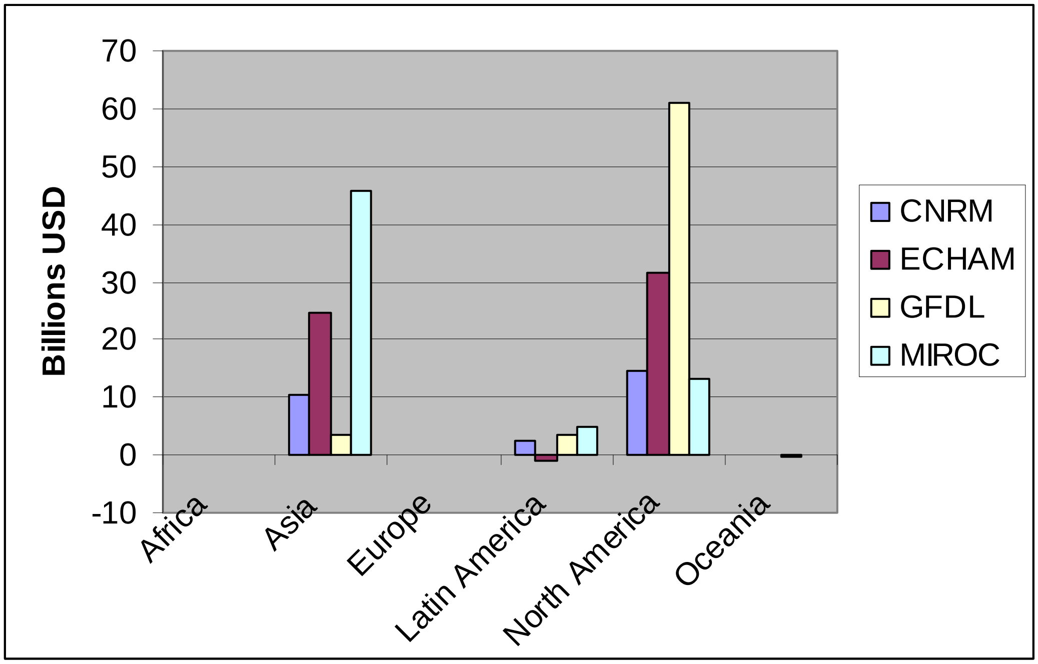


Figure 2: Change in Tropical Storm Power by Ocean Caused by Climate Change



Note: Power is the cube of the maximum wind speed. The change in power is the difference between the power with the future climate and with the current climate.

Figure 3: Climate Change Impacts on Tropical Cyclone Damages by Region by 2100



Note: Calculated using minimum pressure damage model with future baseline.

Figure 4: Tropical cyclone damage in 2100 as a fraction of GDP

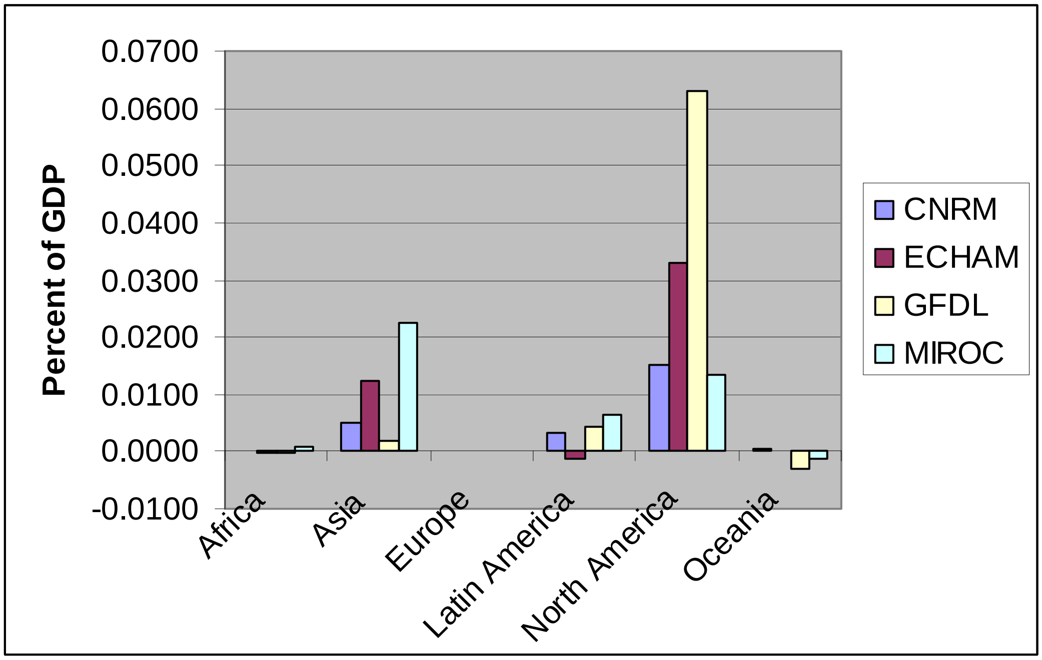
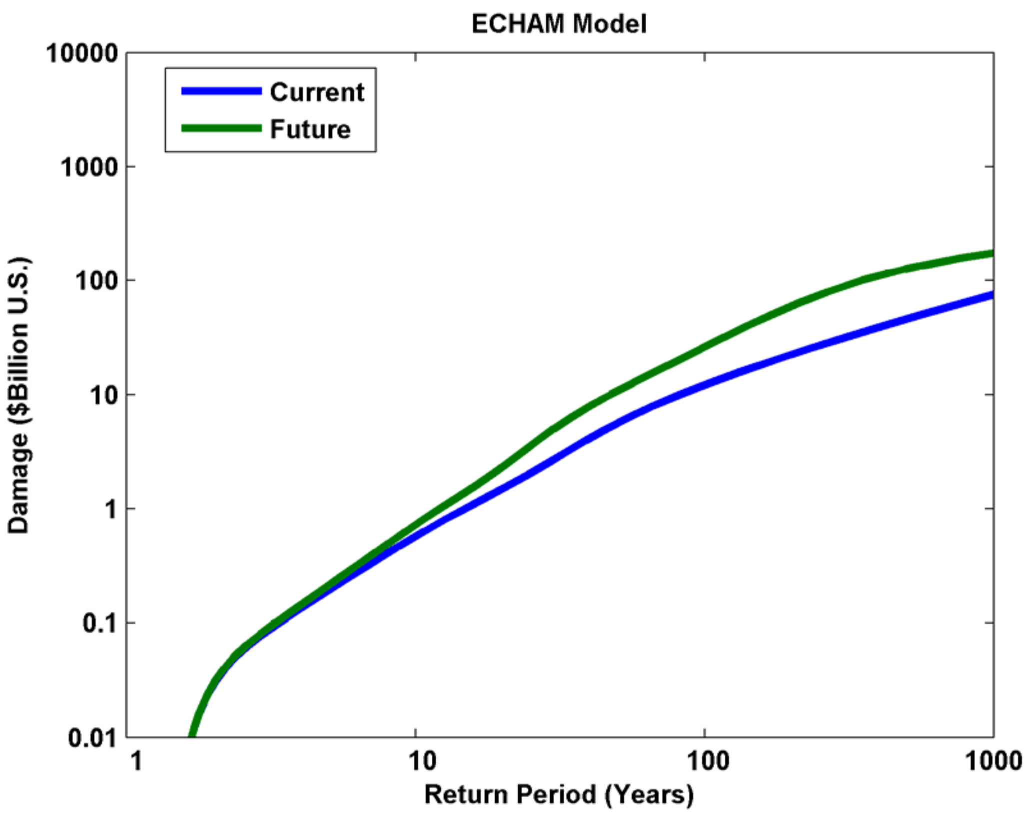


Figure 5: Return period in 2100 by US damage for ECHAM



Note: Damage calculated in 2100.

The Impact of Climate Change on Extreme Events

Robert Mendelsohn
Kerry Emanuel
Shun Chonabayashi
Gokay Saher

Acknowledgements

- Funding by World Bank-United Nations
- Global Facility for Disaster Reduction & Recovery
- Report:
  - Natural Hazards, UnNatural Disasters: The Economics of Effective Prevention
  - Apurva Sanghi

Goal

- Measure how climate change affects future extreme events
- Reflect any underlying changes in vulnerability in future periods
- Estimate damage functions for each type of extreme event
- Measure future extreme events caused by climate change

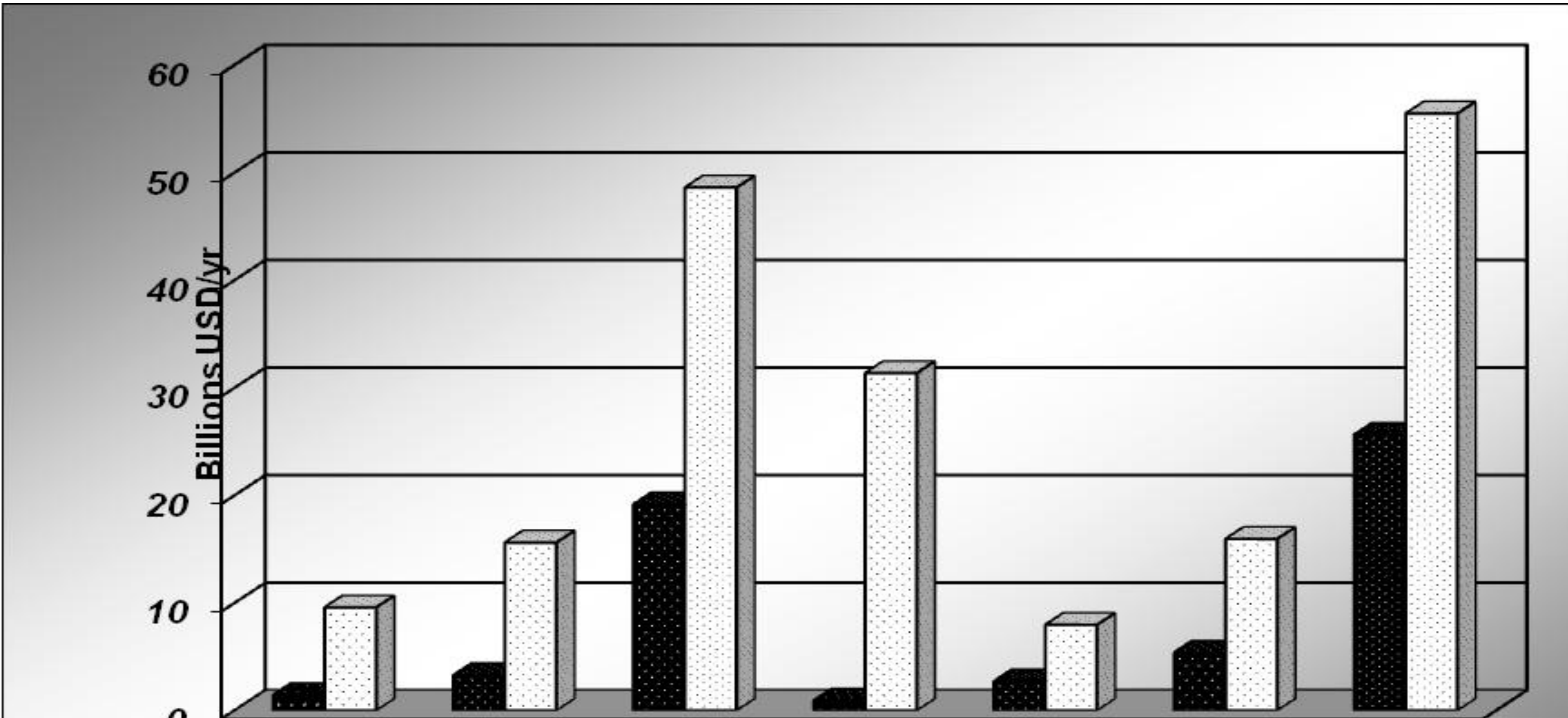
Extreme Events Examined

- Cold Events
- Drought
- Flood
- Hail
- Heat Waves
- Tornadoes
- Thunderstorms
- Tropical cyclones
- Severe Storms (extratropical)

Forecast Future Baseline Impacts

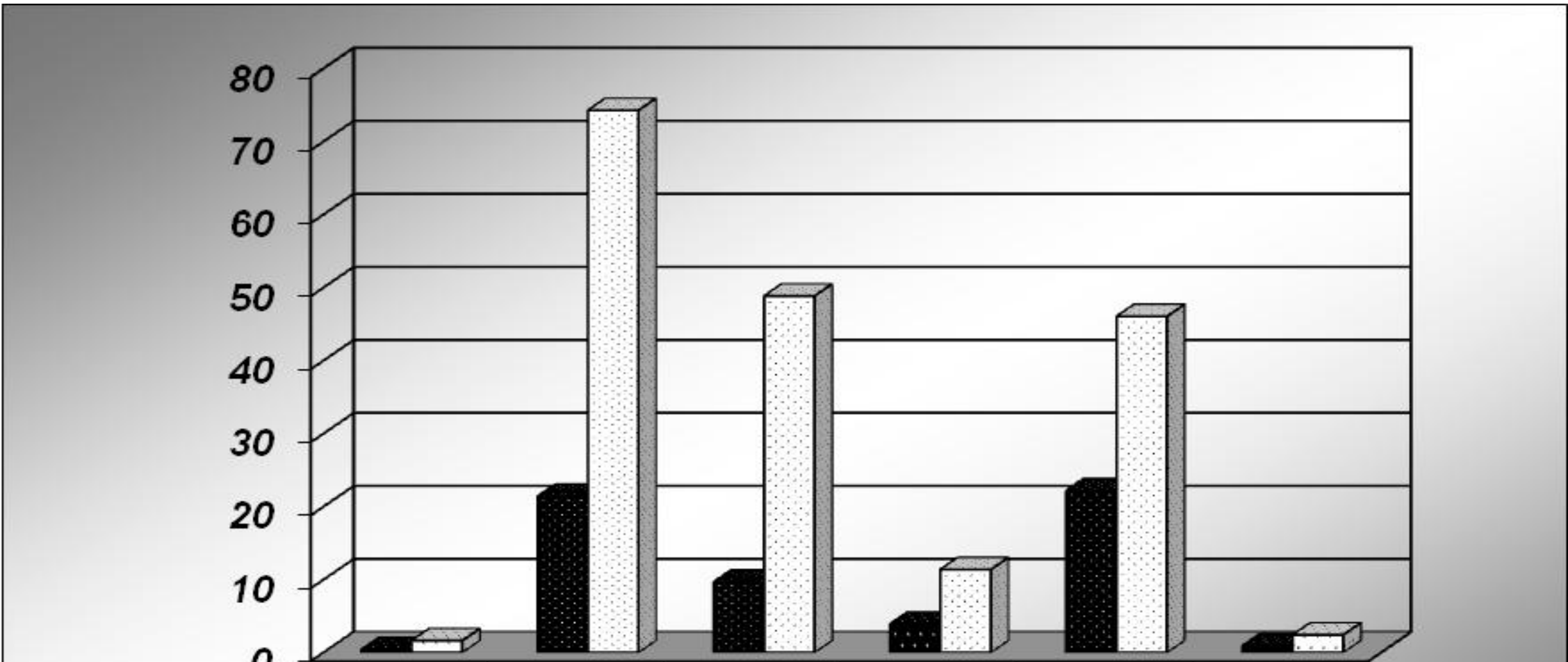
- Estimate damage function with EMDAT data
- Use forecasts of future income and population
- Forecast how damages and deaths will change as income and population increase

Current and 2100 Baseline Impacts of Extreme Weather Events



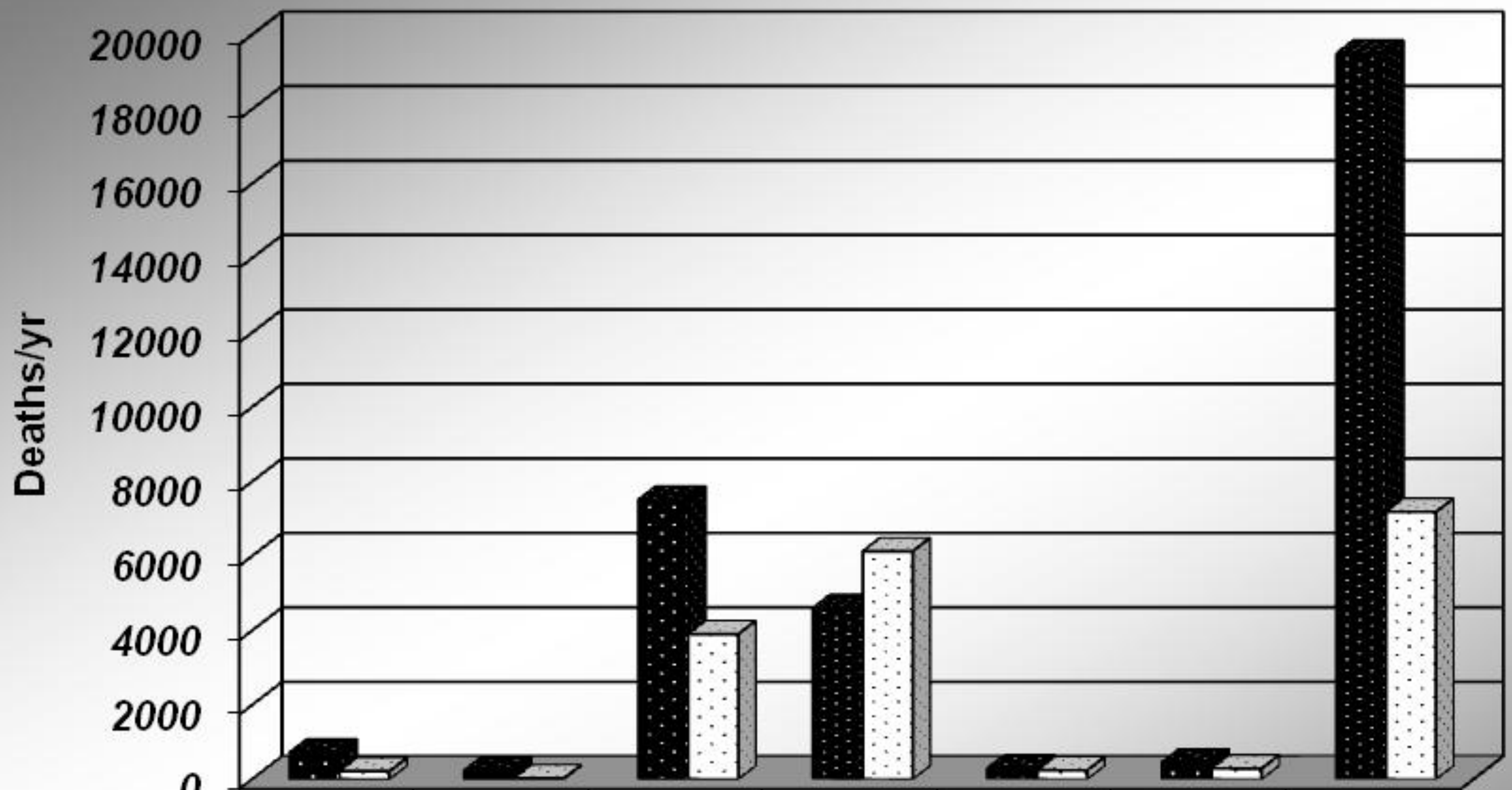
	Cold	Drought	Flood	Heat Wave	Local Storm	Severe Storm	Tropical Cyclone
■ 2010	1	3	19	1	3	5	26
□ 2100	10	16	49	31	8	16	55

Extreme Event Damages by Region



	Africa	Asia	Europe	Latin America	North America	Oceania
2010	0	21	10	4	22	1
2100	2	74	49	11	46	2

Current and Future Deaths by Extreme Event



	Cold	Drought	Flood	Heat Wave	Local Storm	Severe Storm	Tropical Cyclone
■ 2010	716	234	7508	4598	295	451	19486
□ 2100	215	25	3898	6123	239	287	7180

Past Climate Results

- IPCC 1996 guesses CC increases US tropical cyclone damages by 0.02% of GDP and world damages of 0.002% of GWP
- Nordhaus 2006 estimates CC doubles US tropical cyclone damages (0.06% of GDP)
- Narita et al 2007 estimate CC doubles world tropical cyclone damages by 0.006% GWP
- Stern guesses CC increases all extreme event damages by 5% of GWP

Integrated Assessment Model

Emissions Trajectory

↓

Climate Scenario

↓

Event Risks

↓

Vulnerability Projection

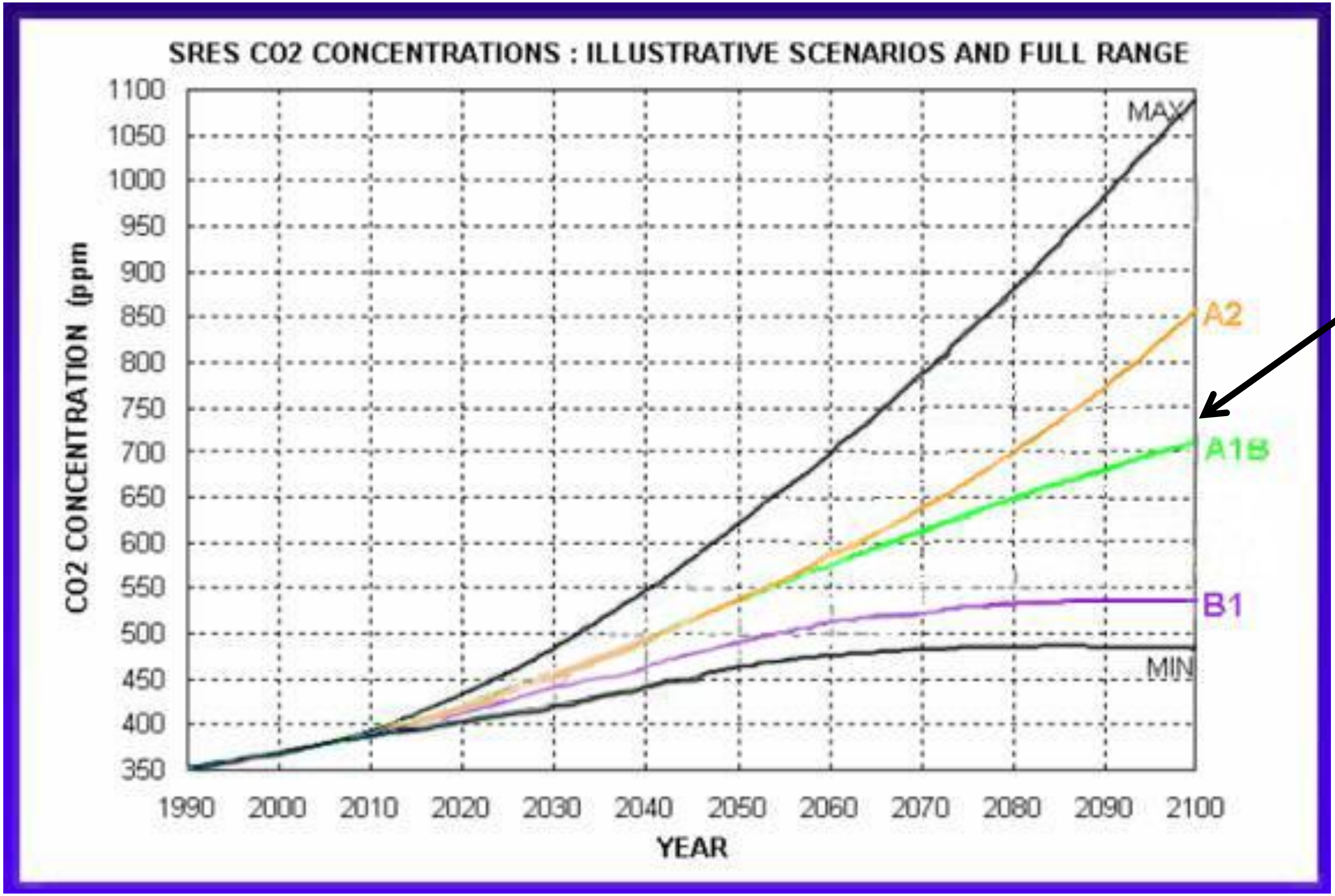
↓

Damage Function

↓

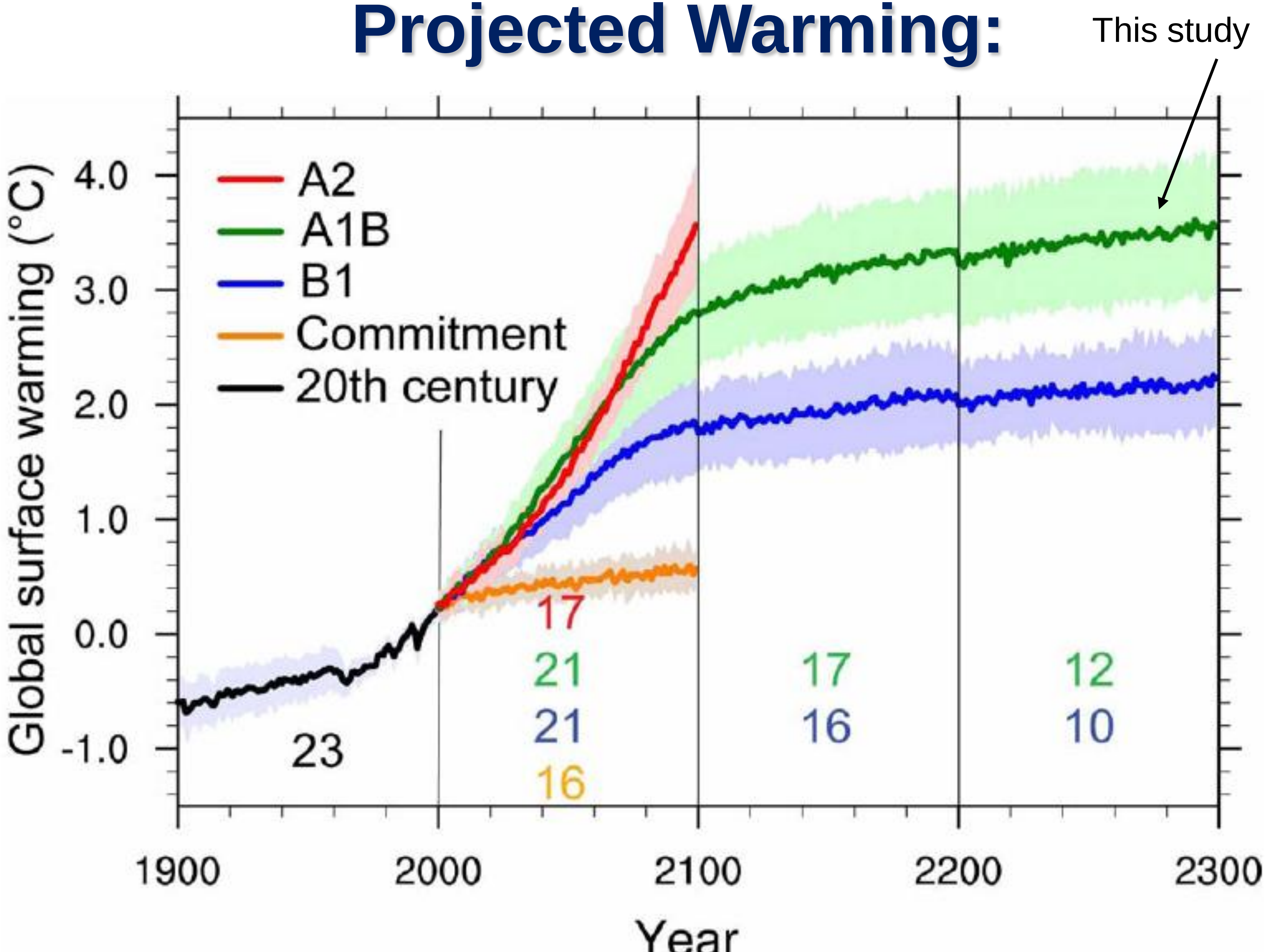
Damage Estimate

IPCC Emissions Scenarios



This study

Projected Warming:



Using Climate Models to Estimate Changing Incidence of Extreme Events

- Some events can be inferred directly from climate model output
  - Heat waves and cold snaps
  - Droughts and certain kinds of floods
  - Large-scale non-tropical wind storms
- Some must be inferred indirectly, by using sub-models (e.g. “downscaling”)
  - Tropical cyclones, thunderstorms, tornadoes, hail storms

Climate Models

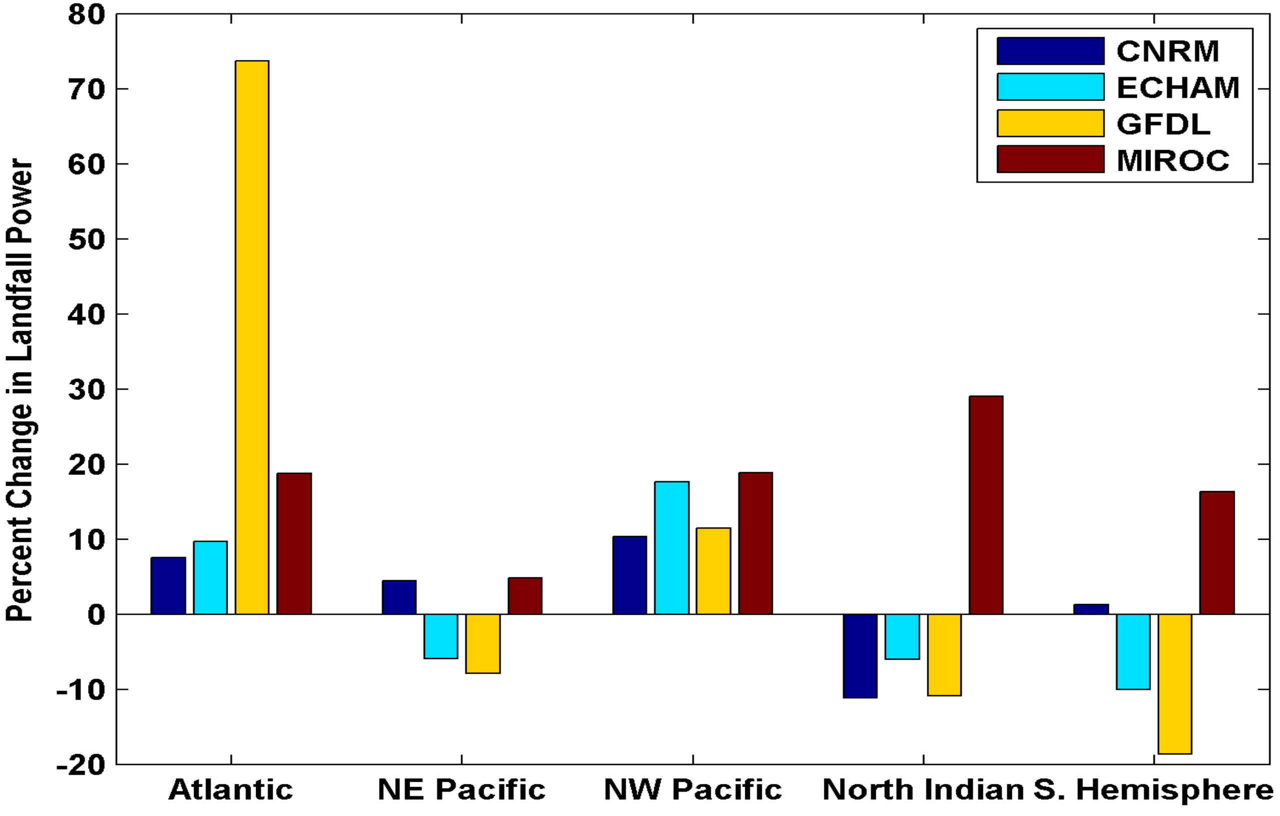
- CNRM
- ECHAM
- GFDL
- MIROC (tropical cyclones only)

Tropical Cyclone Generator

- **Step 1**: Seed each ocean basin with a very large number of weak, randomly located cyclones
- **Step 2**: Cyclones are assumed to move with the large scale atmospheric flow in which they are embedded, taken from the global climate model
- **Step 3**: Run a detailed cyclone intensity model for each event, and note how many achieve at least tropical storm strength
- **Step 4:** Using the small fraction of surviving events, determine storm statistics.

Details: Emanuel et al., Bull. Amer. Meteor. Soc., 2008

Tropical Cyclone Power by Ocean Basin



US Tropical Cyclone Damage Function

	Constant	Minimum Pressure	Income	Populat. Density
Damage Model	607.5 (10.39)	-86.3 (9.96)	0.370 (0.45)	0.488 (1.53)
Fatality Model	247.5 (4.10)	-33.3 (3.69)	-2.35 (1.74)	1.28 (2.78)

International Tropical Cyclone Damage Function

	Constant	Income	Populat. Density
Damage	15.17 (22.77)	0.415 (6.44)	-0.21 (3.04)
Fatality	6.25 (18.20)	-0.477 (14.01)	0.07 (1.86)

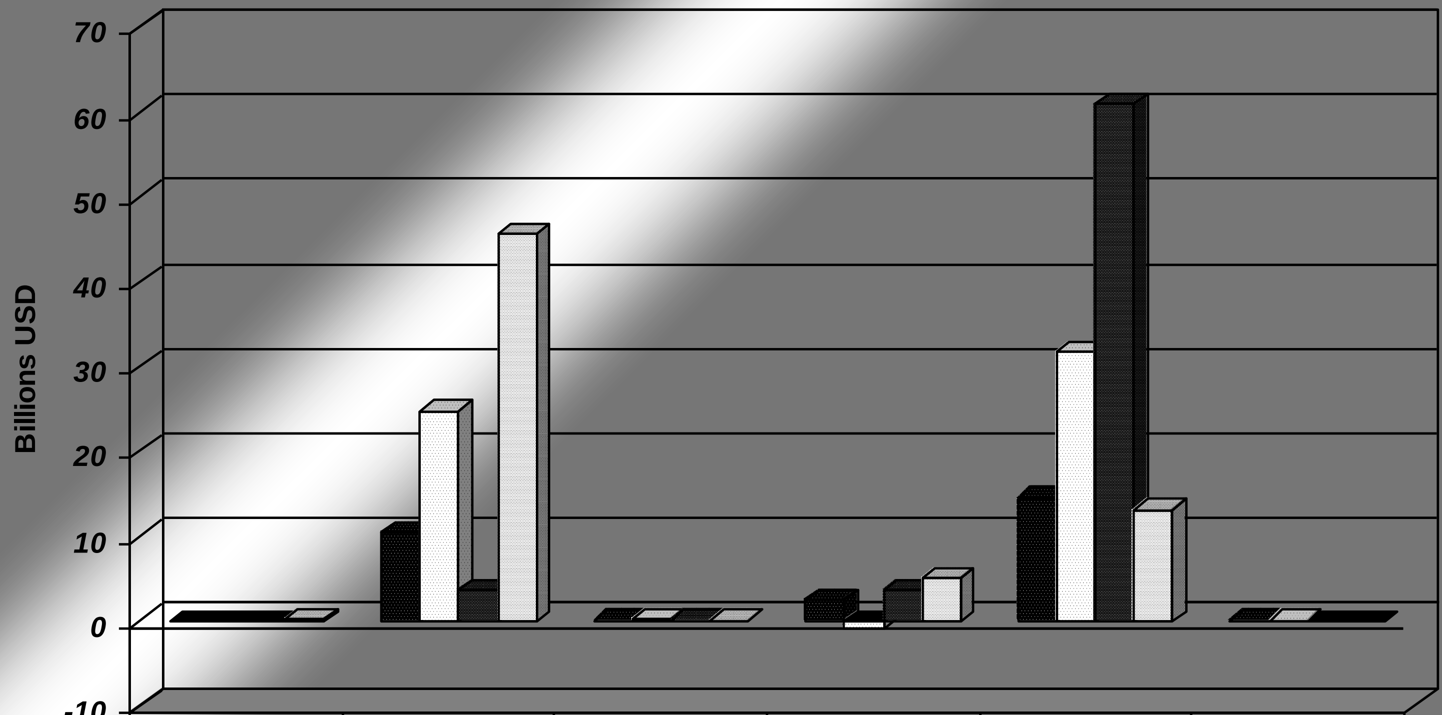
Baseline Tropical Cyclone Global Damages

- Current Damages: $26 billion/yr
- Future Damages: $55 billion/yr
- Current Global Deaths: 19,500/yr
- Future Global Deaths: 7,200/yr
- Change in 2100 because of higher population and income
- Current climate for baseline estimates

Climate Change Impacts on Tropical Cyclones in 2100

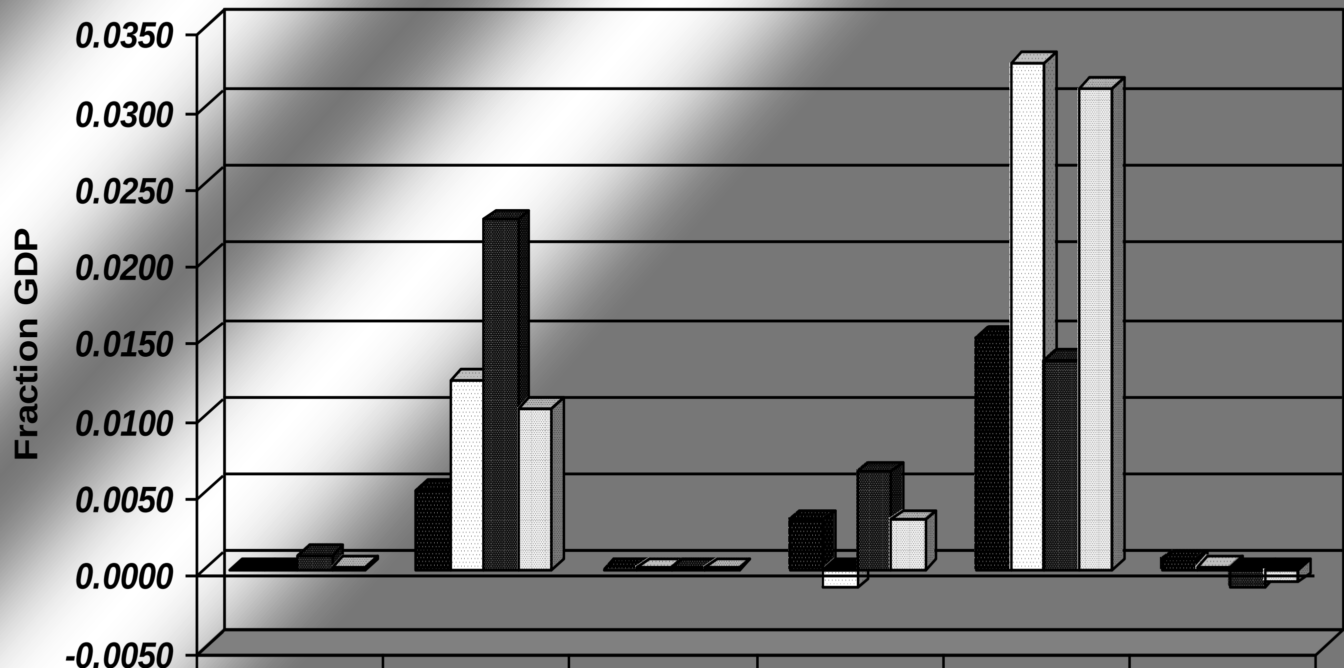
	CNRM	ECHAM	GFDL	MIROC
Damages (billions)	$19.9	$54.7	$70.2	$69.7
Deaths	760	-1500	-3300	1300

Impact of Climate Change on Regional Cyclone Damage



	Africa	Asia	Europe	Latin America	North America	Oceania
CNRM	0	10	0	3	15	0
ECHAM	0	25	0	-1	32	0
GFDL	0	4	0	4	61	0
MIROC	0	46	0	5	13	0

Climate Change Cyclone Impacts as a Percent of GDP

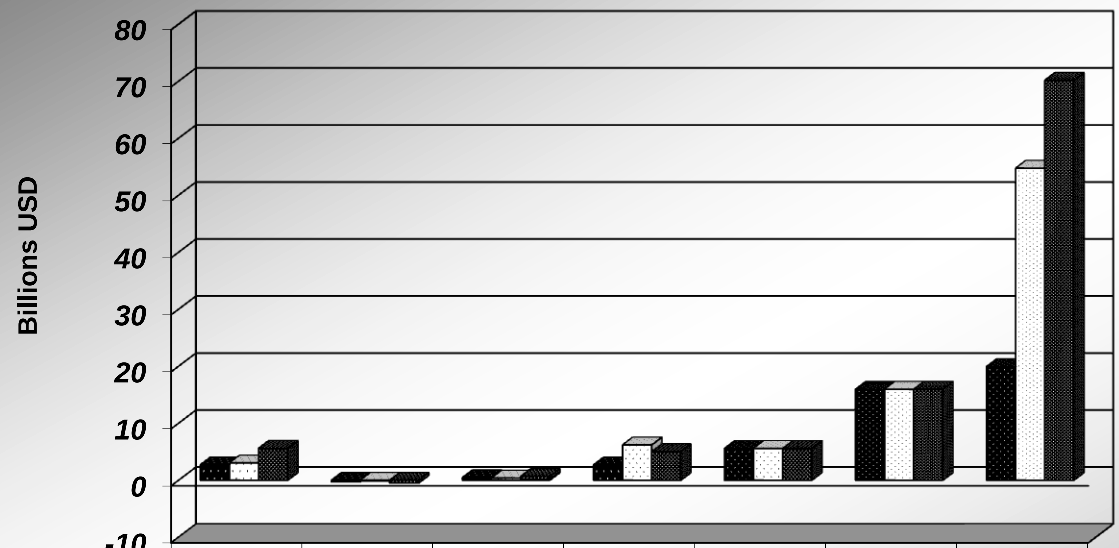


	Africa	Asia	Europe	Latin America	North America	Oceania
CNRM	0.0000	0.0051	0.0000	0.0032	0.0150	0.0006
ECHAM	-0.0001	0.0122	0.0000	-0.0012	0.0328	0.0002
GFDL	0.0009	0.0226	0.0000	0.0063	0.0136	-0.0011
MIROC	0.0002	0.0104	0.0000	0.0032	0.0311	-0.0009

Climate Change Impact by 2100 on All Extreme Events

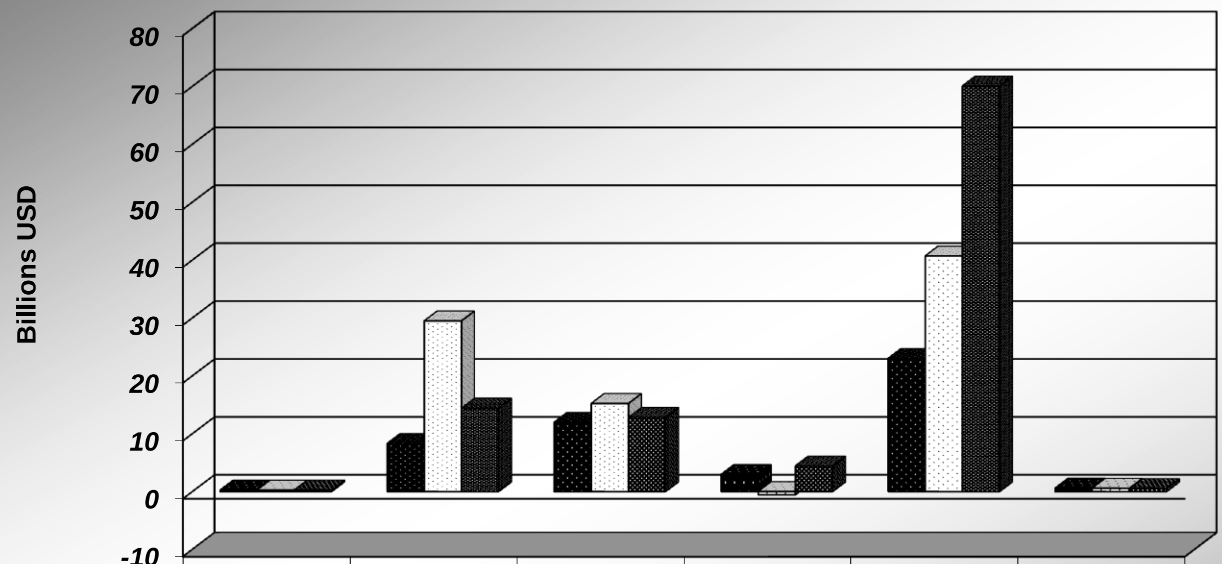
	CNRM	ECHAM	GFDL
Damages ($billion/yr) (%GDP)	$47.0 (0.008%)	$85.6 (0.015%)	$102.5 (0.018%)
Deaths (per year)	1750	-500	-2277

Climate Change Damages by Event



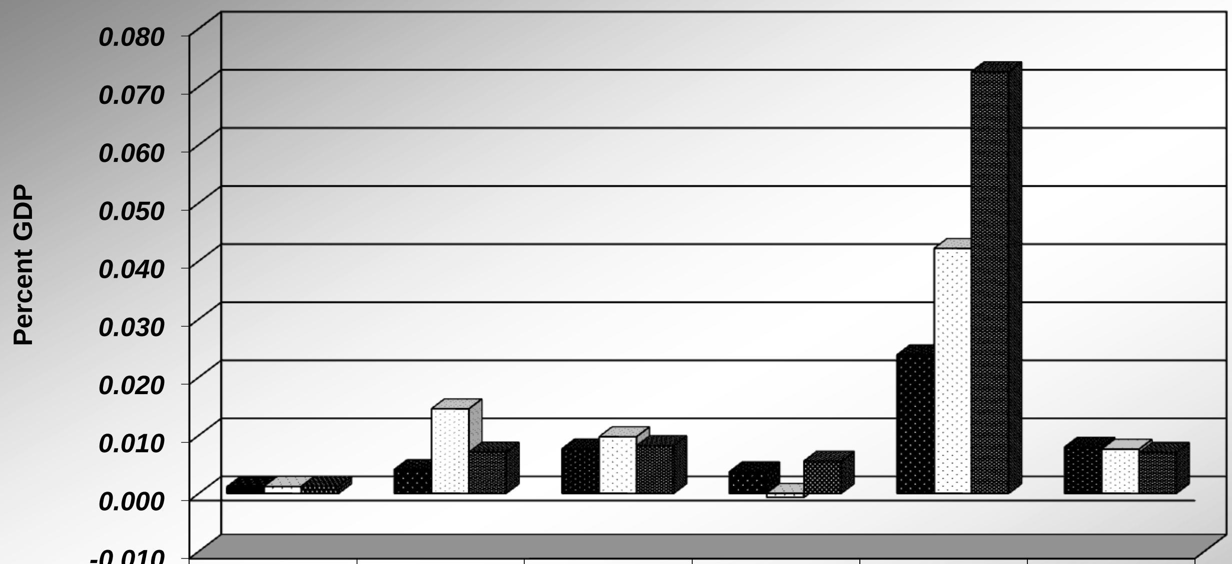
	Cold	Drought	Flood	Heat	Local Storms	Severe Storms	Tropical Cyclone
CNMR	3	0	0	3	6	16	20
ECHAM	3	0	0	6	6	16	55
GFDL	6	0	1	5	6	16	70

Climate Change Extreme Event Damages by Region



	Africa	Asia	Europe	Latin America	North America	Oceania
CNMR	0	8	12	3	23	1
ECHAM	0	29	15	-1	41	1
GFDL	0	14	13	4	70	1

Climate Change Extreme Event Damages in % GDP



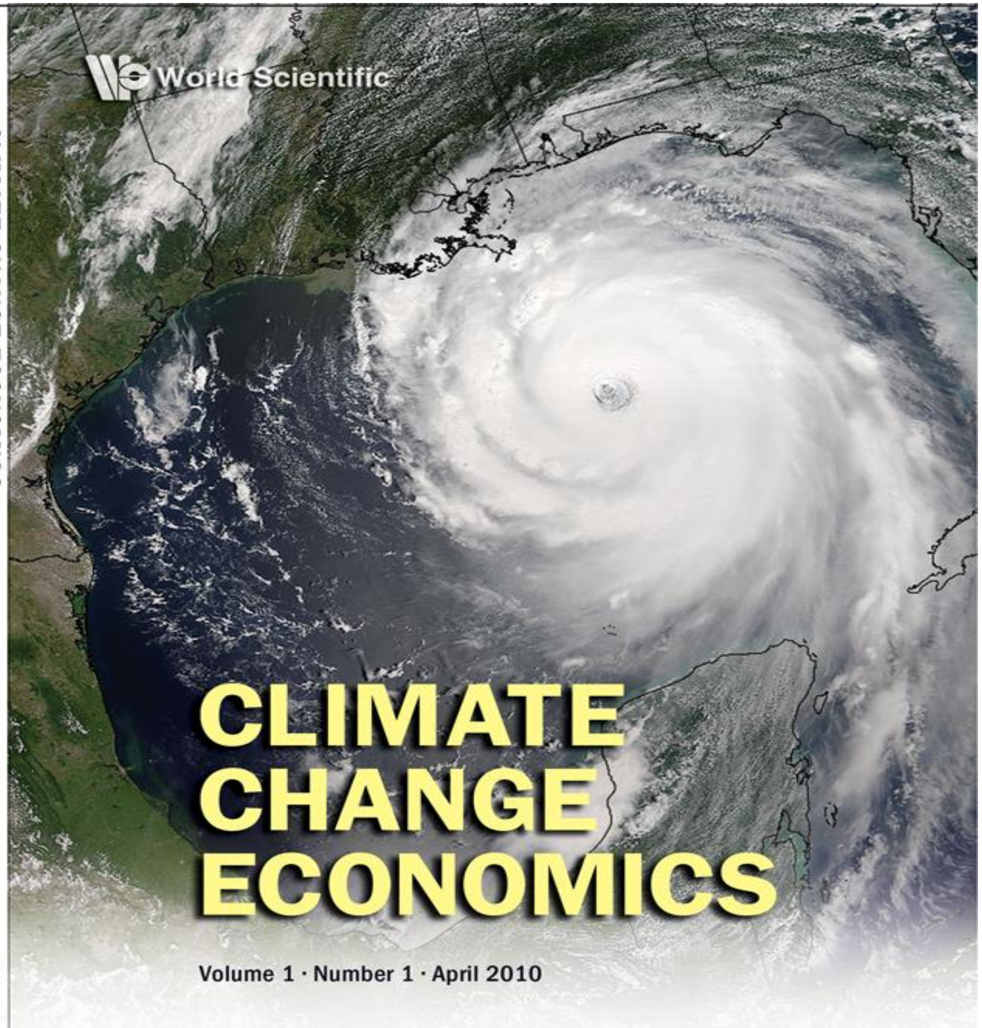
	Africa	Asia	Europe	Latin America	North America	Oceania
CNMR	0.001	0.004	0.008	0.004	0.024	0.008
ECHAM	0.001	0.015	0.010	-0.001	0.042	0.008
GFDL	0.001	0.007	0.008	0.006	0.073	0.007

Limitations

- Non hurricane impacts uncertain
- Country scale may be too coarse- need finer scale
- Need better data about damages and extreme events
- Ecosystem effects are not measured
- Adaptation is not explicitly modeled

Summary

- Predicted climate change impacts from all extreme events (including tropical cyclones) range from $47 to $100 billion/yr by 2100
- Equivalent to 0.008 to 0.018 percent of GWP by 2100
- Climate change has mixed effect on fatalities because tropical cyclone deaths may fall more than other deaths increase



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Editor-in-Chief:
Robert Mendelsohn
Yale University, USA

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Incorporating Water Resources Impacts in Integrated Assessment Models

Kenneth Strzepek

Joint Program on the Science and Policy of Global Change

MASSACHUSETTS INSTITUTE OF TECHNOLOGY






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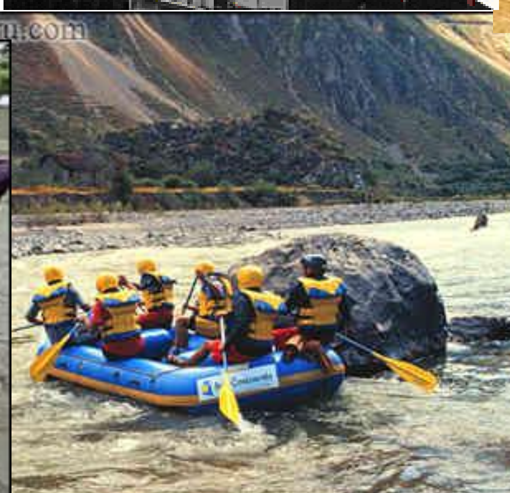
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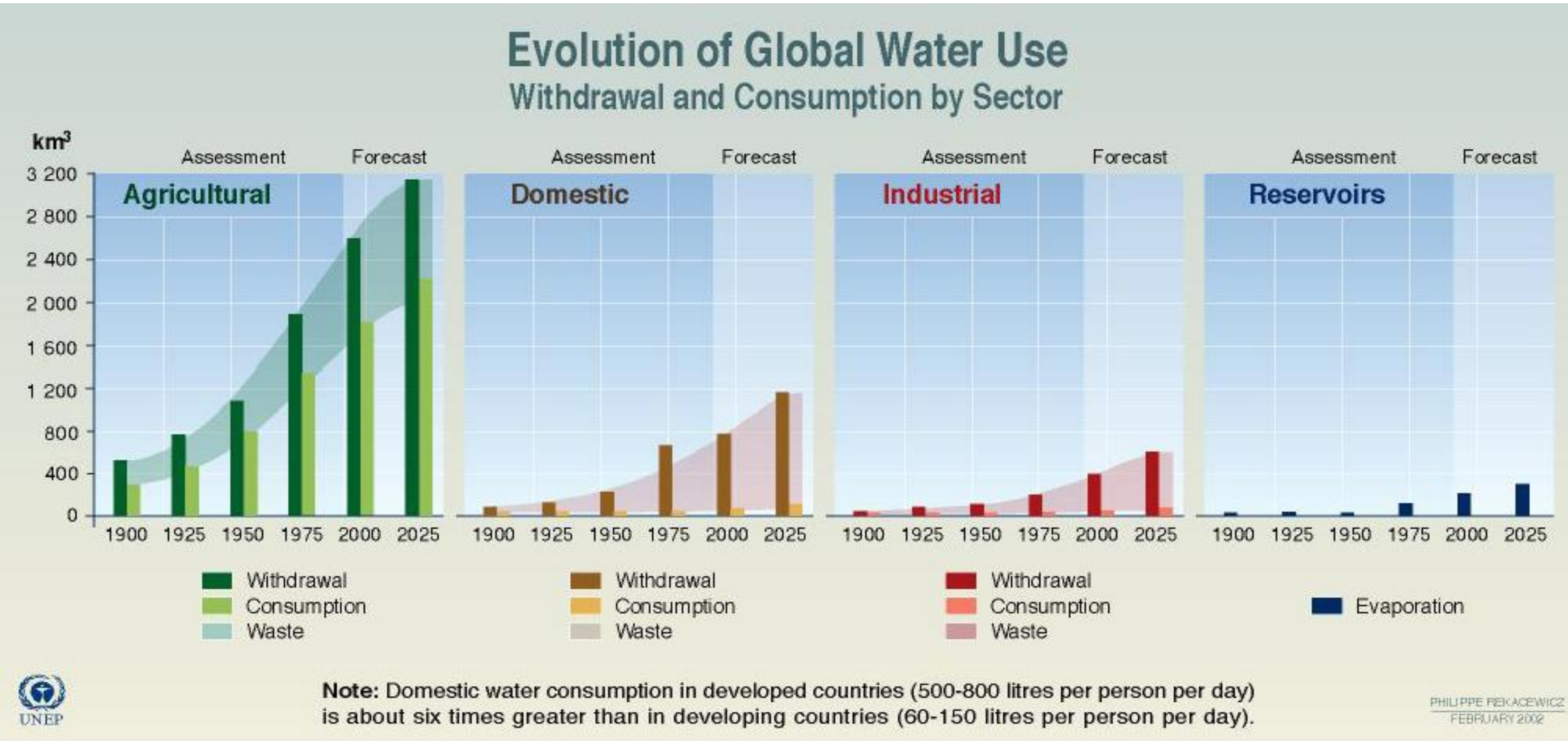
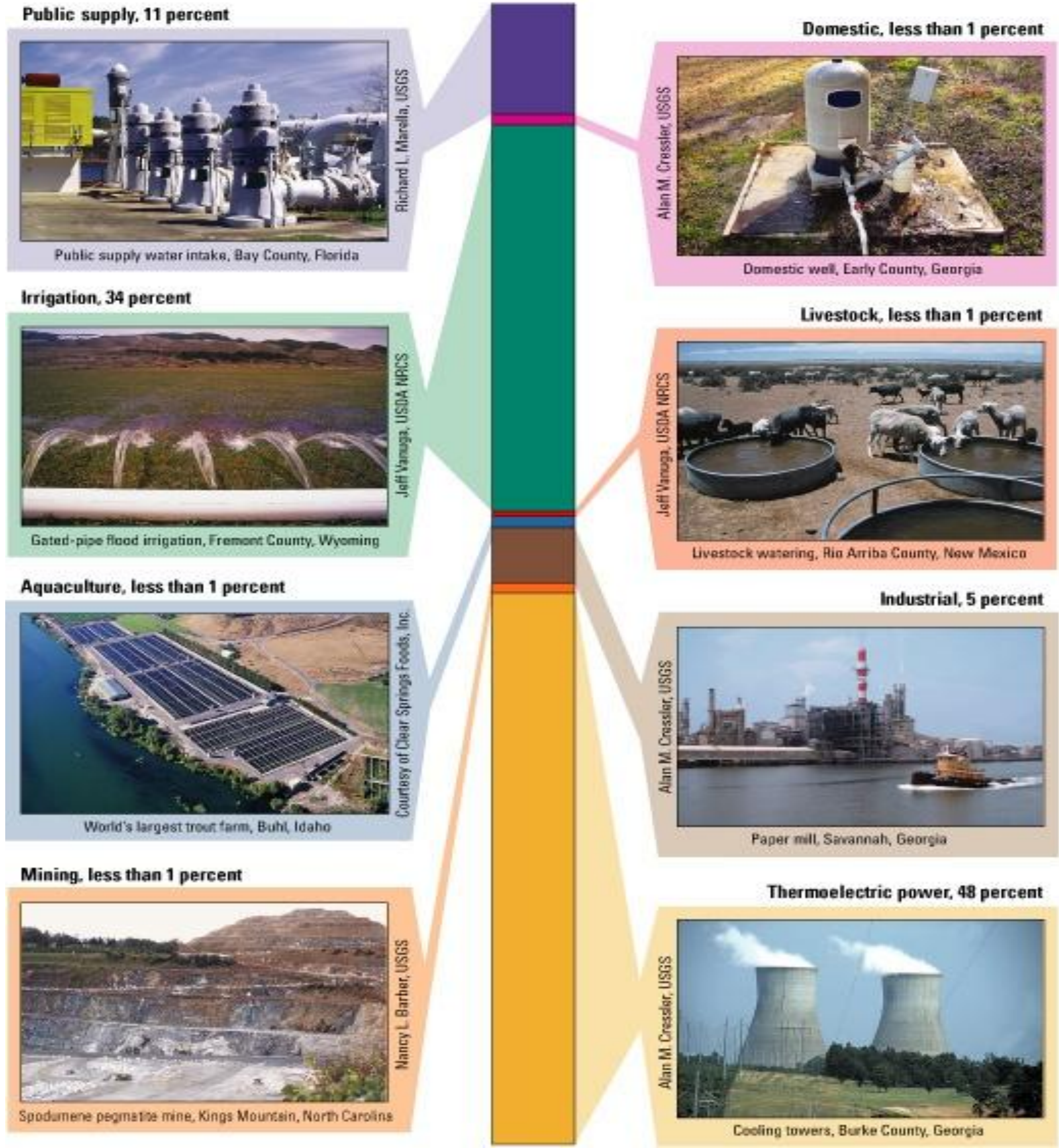
Elements of the Water System

- The Hydrologic System
  - Climate and Land Use
- The Managed Water Supply System
- Water Demand
  - Aquatic Ecosystem
  - Market Activities
  - Human Health
  - Non-Market Activities
- Excess Water
- Role in Economic Development

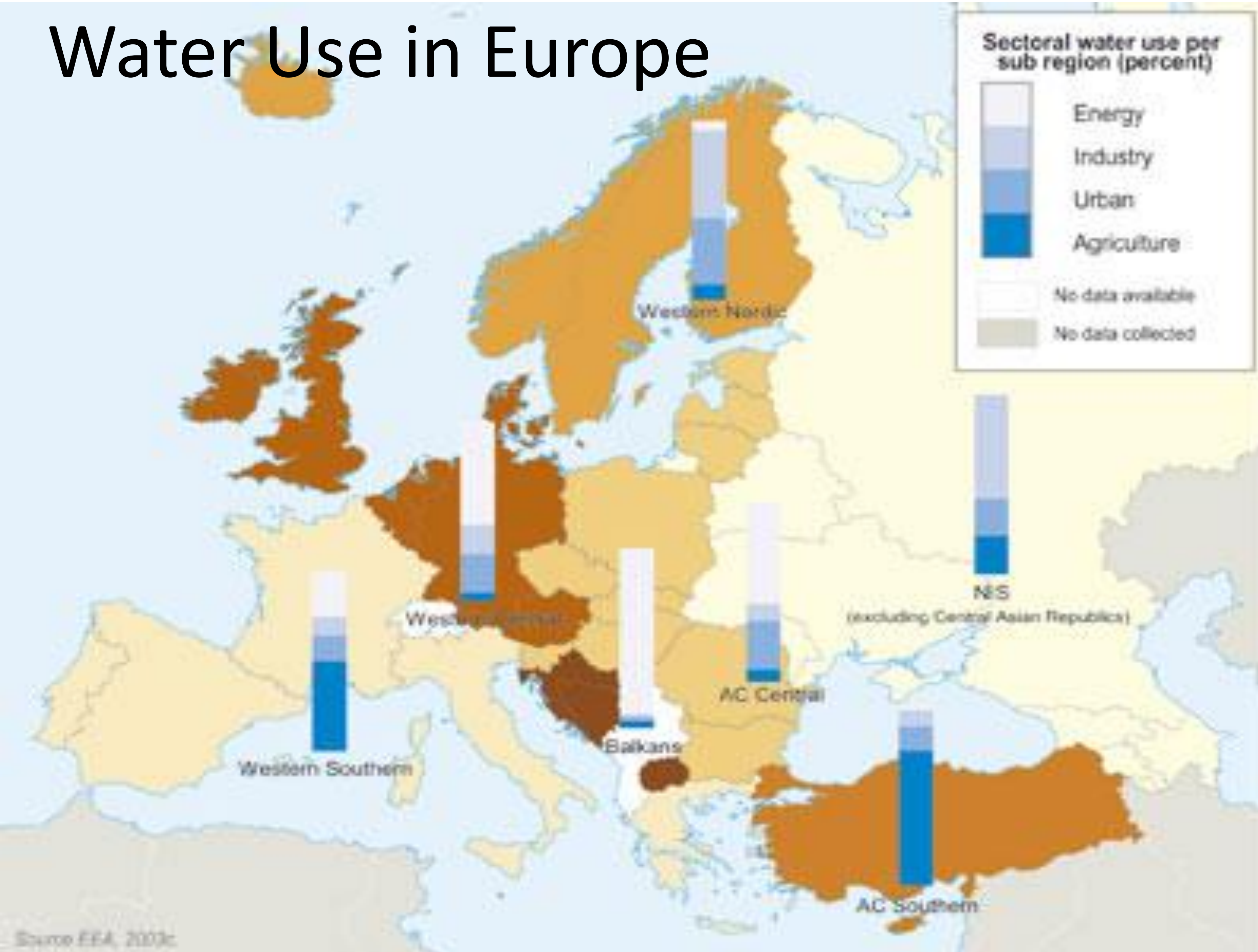


Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational,Scientific and Cultural Organisation (UNESCO, Paris), 1999.

United States Water Use 2005



Water Use in Europe



Modeling Water Resources Impacts in IAMS

- **We know how to model key water related at the River Basin Level**

Hydrology, Crops, Energy, M&I, ….

Combined Use of Optimization and Simulation Models in River Basin Planning

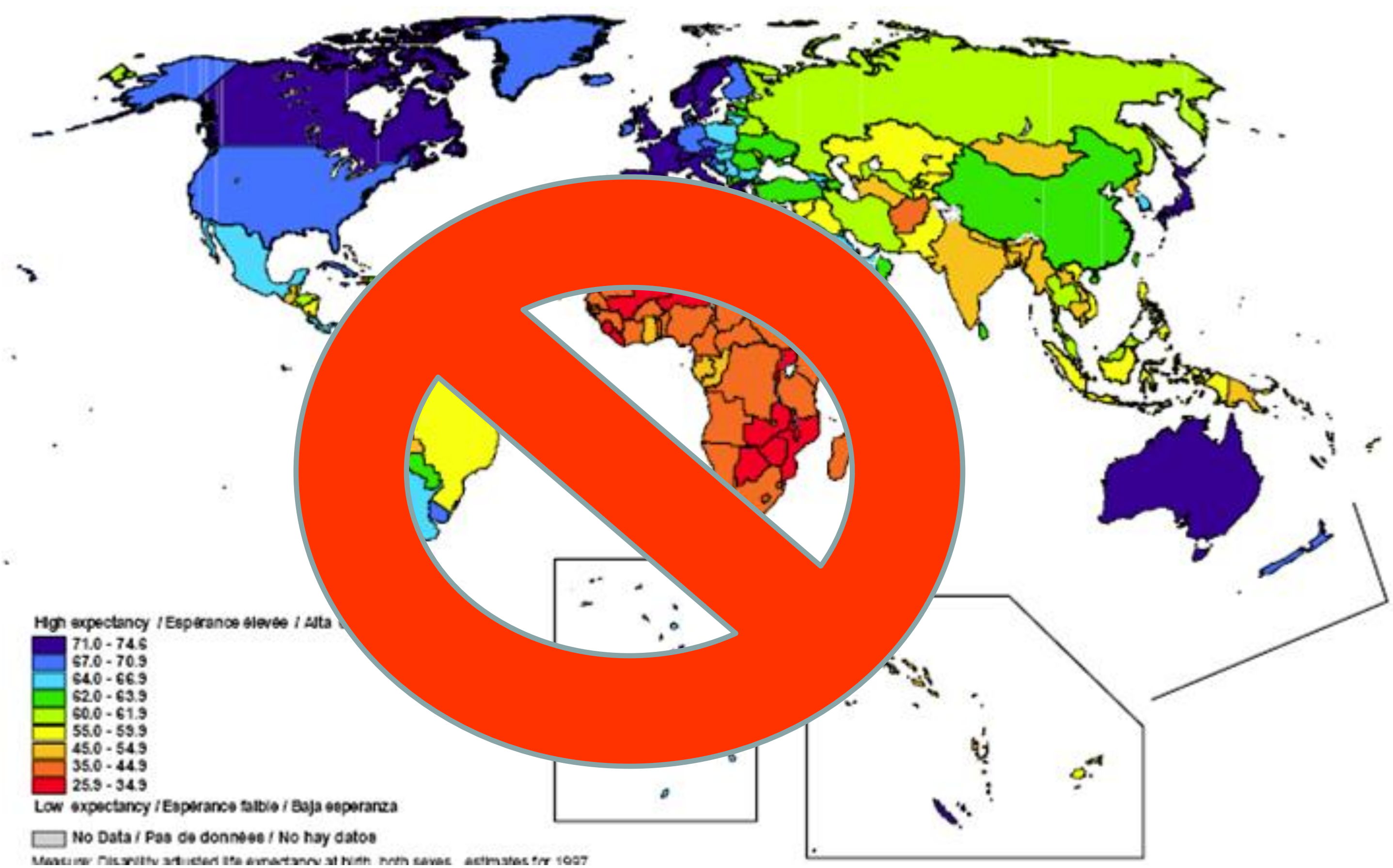
Henry D. Jacoby & D. P. Loucks *WATER RESOURCES RESEARCH, VOL. 8, NO. 6,, 1972*

- What is the appropriate Spatial and Temporal Scale to accurately model climate change impacts for the questions being asked by IAMs or sectoral level analysis at what scale.
- IAMs
  - Spatial Scale: 10 to 20 regions: National lowest Scale
  - Temporal Scale: 1 to 5 year time steps
- Global Crop and Hydrologic Modeling at 0.1 to 0.5 degree dail
- There are over 10,000 level 4 River Basin "~20,000 km2"
- Water Mgt Models : "River Basin Scale" and Monthly

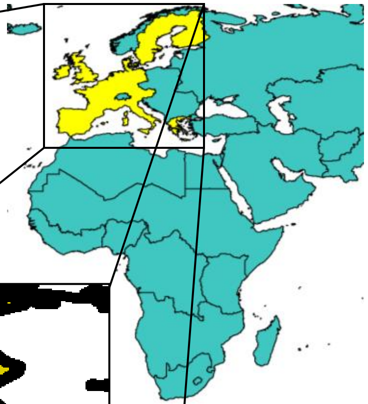
Spatial Scale Economic Components of Selected IAMs

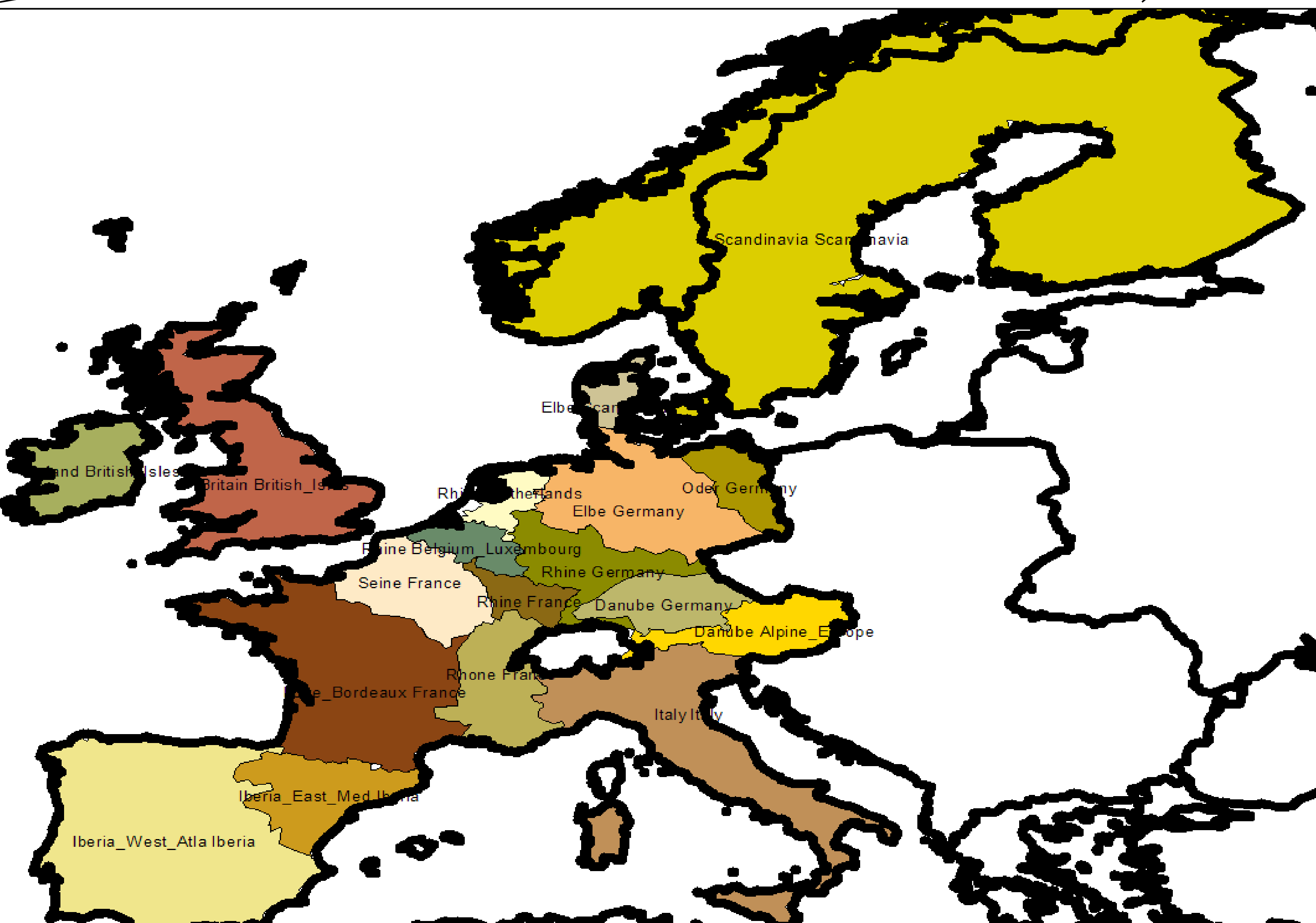
- MiniCAM: 14 Regions
  - the United States, US, Canada, W. Europe, Australia & New Zealand, Japan, Eastern Europe, The Former Soviet Union, China, Mid-East, Africa, Latin America, Korea, Southeast Asia, and India. In addition, three others are under development: Mexico, Argentina, and Brazil.
- MERGE: 9 Regions
  - Canada, Australia and New Zealand (CANZ); China; eastern Europe and the former Soviet Union (EEFSU); India; Japan; Mexico, and OPEC (MOPEC); western Europe (WEUR); the United States of America (USA); and the rest of the world (ROW).
- IGSM/EPPA: 16 Regions
  - United States (USA) European Union (EUR) Eastern Europe (EET) Japan (JPN) Former Soviet Union (FSU) Australia & New Zealand (ANZ) Canada (CAN China (CHN) India (IND) Higher Income East Asiad(ASI) Middle East (MES) Indonesia (IDZ) Mexico (MEX) Central & South America (LAM) Africa (AFR) Rest of World (ROW)
- Fund : National Level

Global Water and AG IMPACTS Regional and National Scale

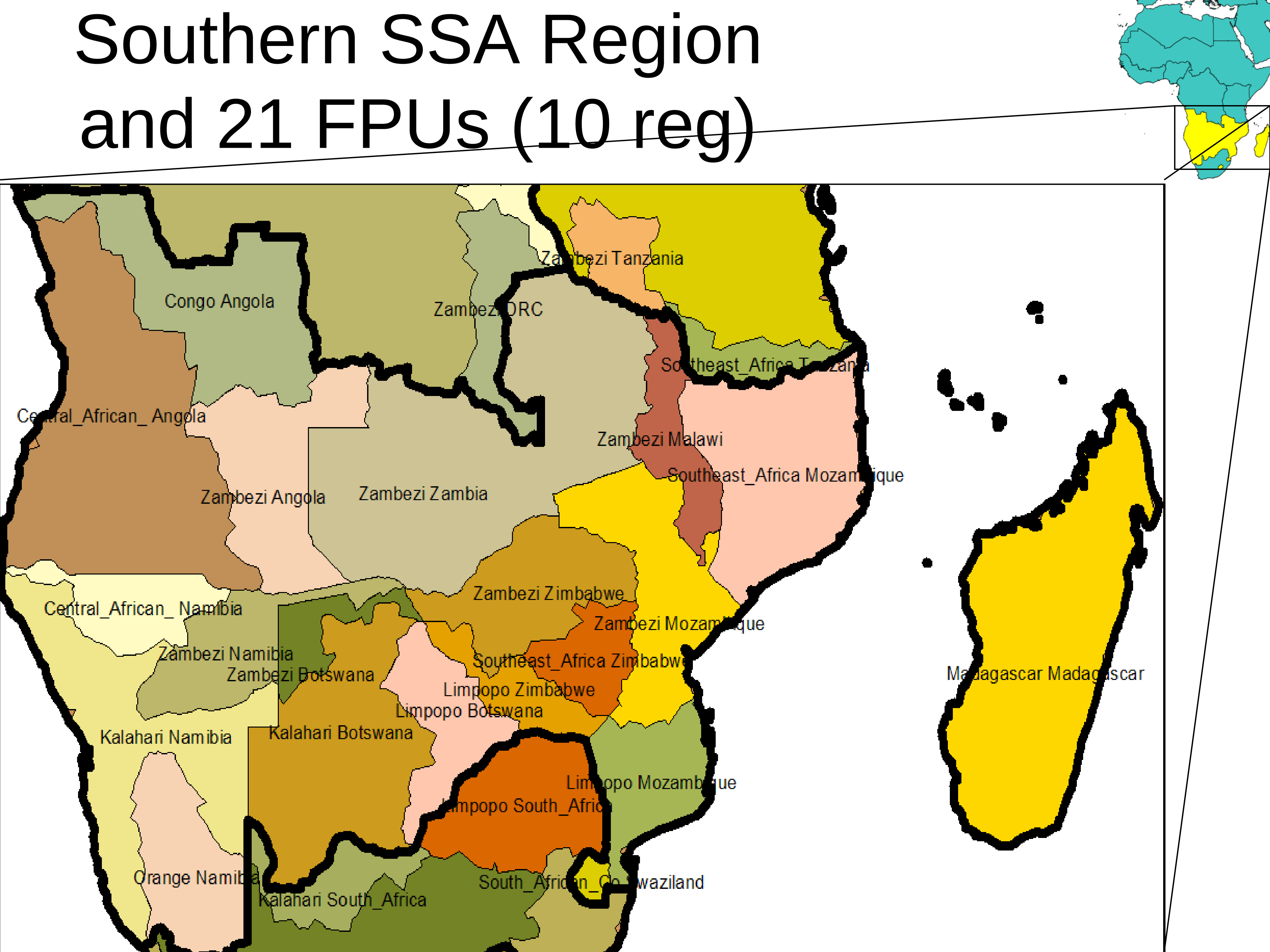


Europe Region and 18 FPUs (9 reg)

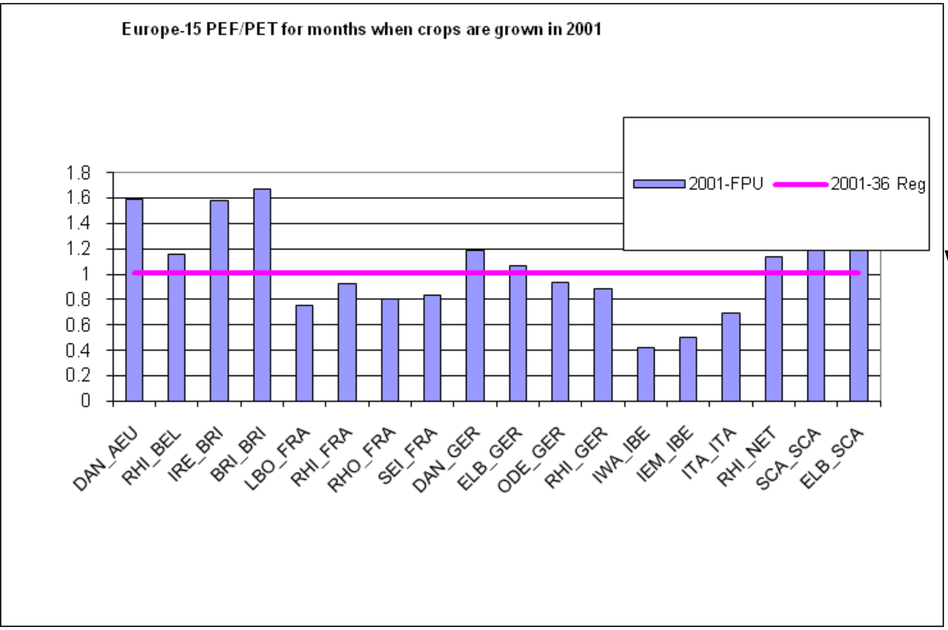




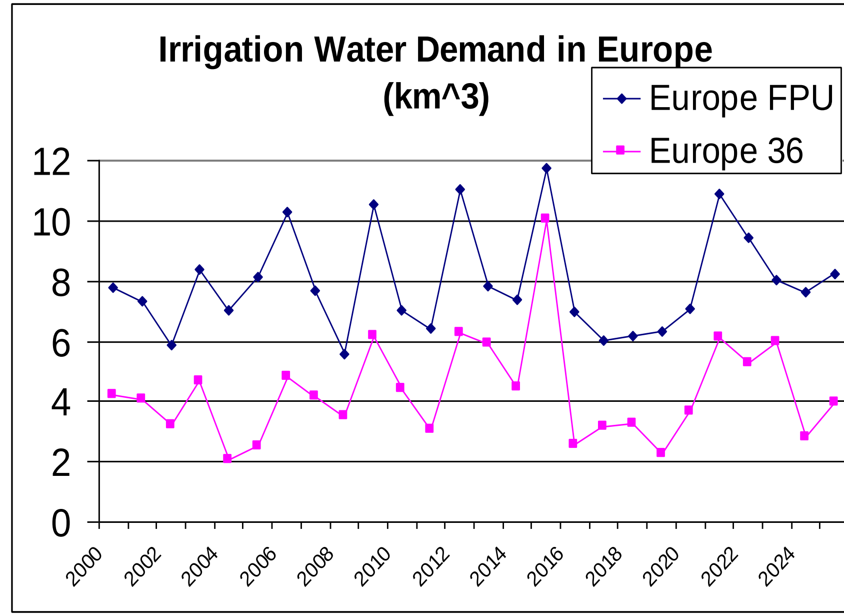
Southern SSA Region and 21 FPUs (10 reg)

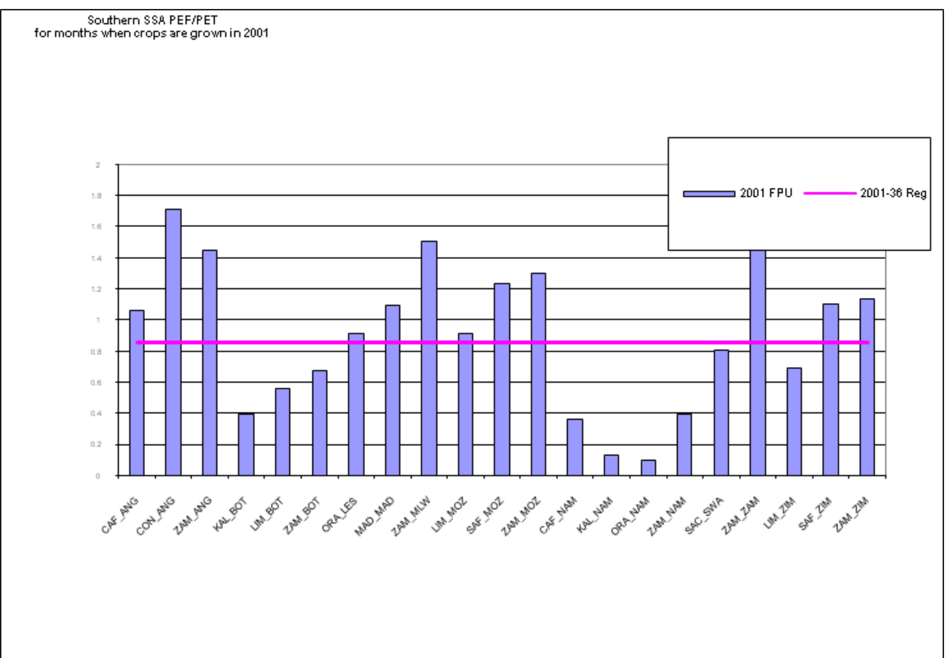


Irrigation Water Demand

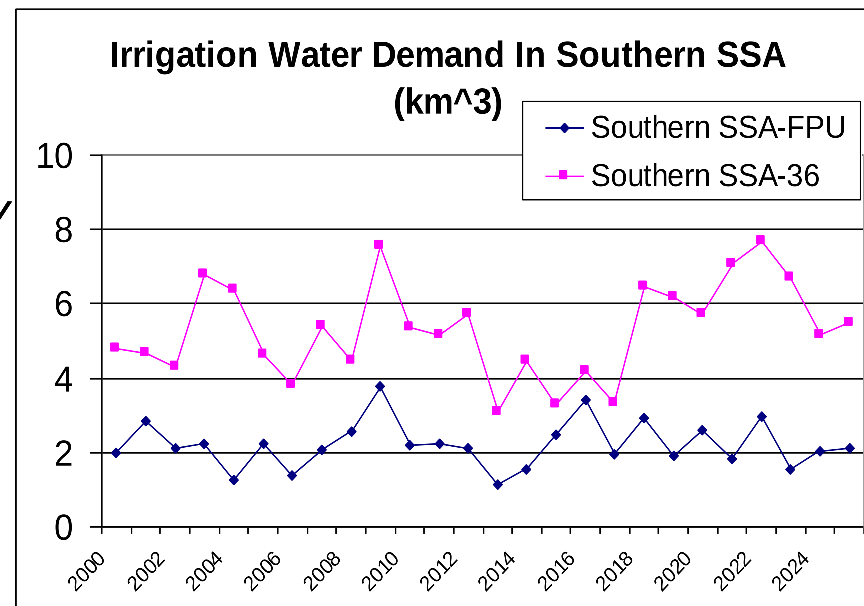


WET

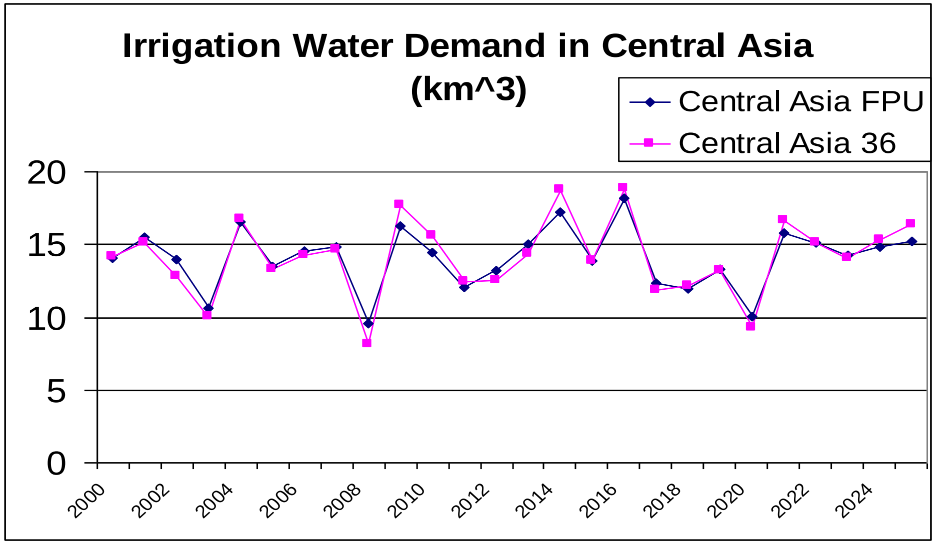


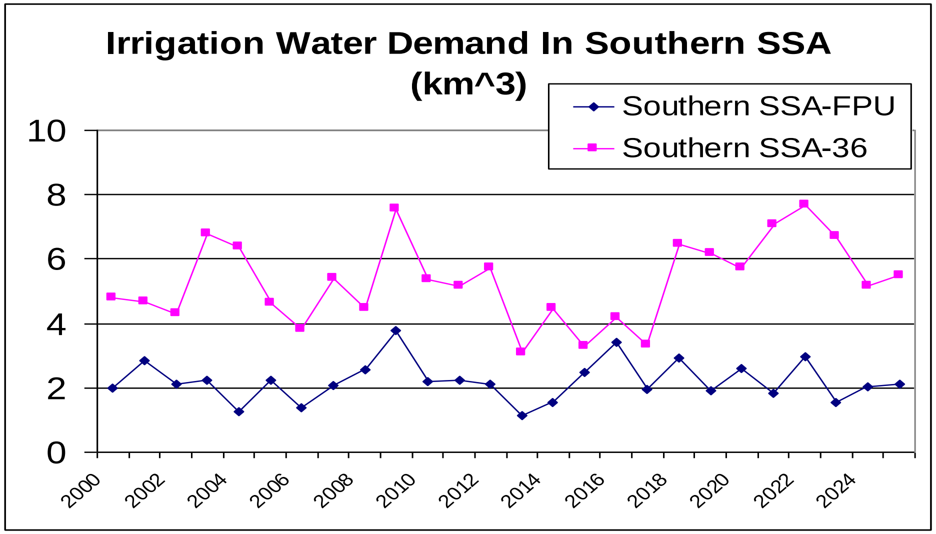


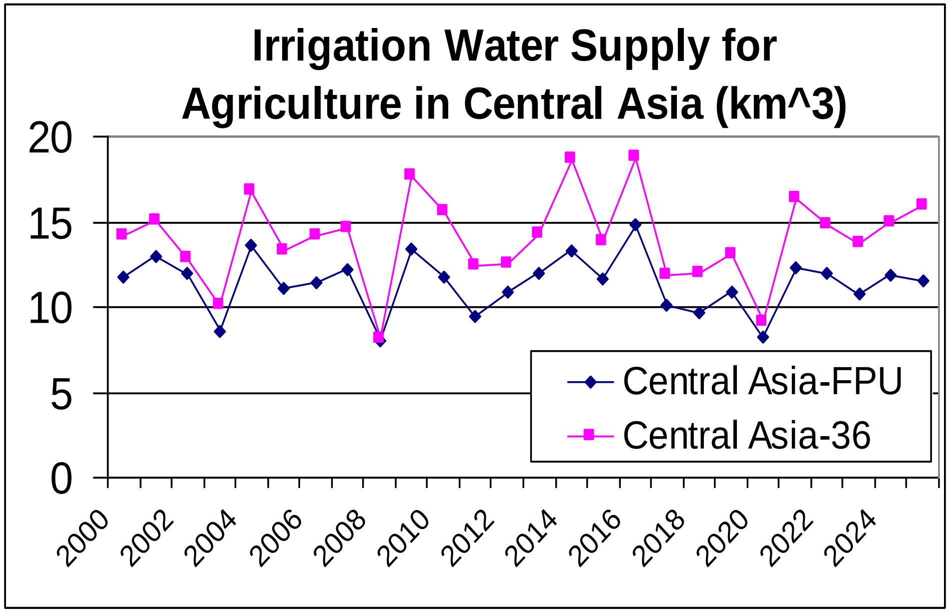
DRY

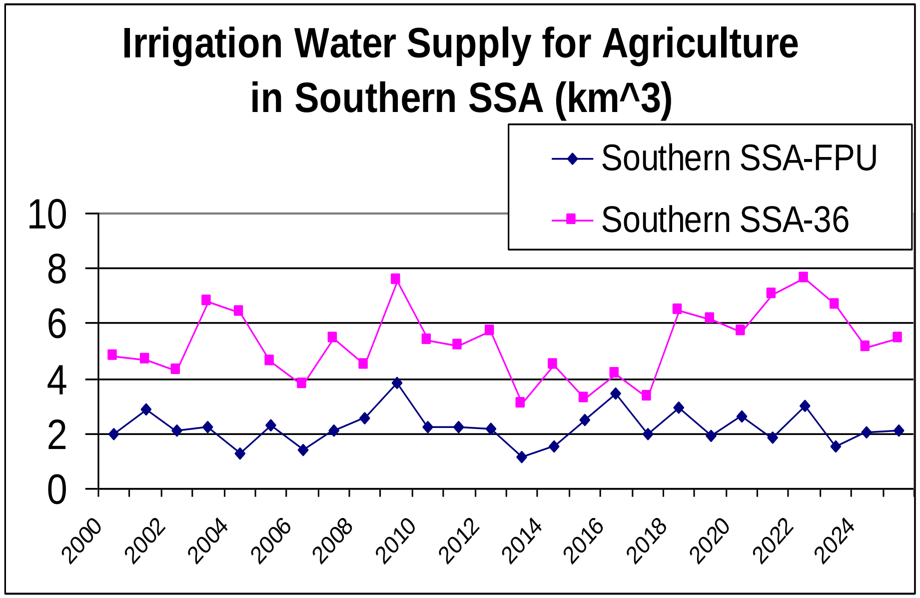


Irrigation Water Supply for Agriculture





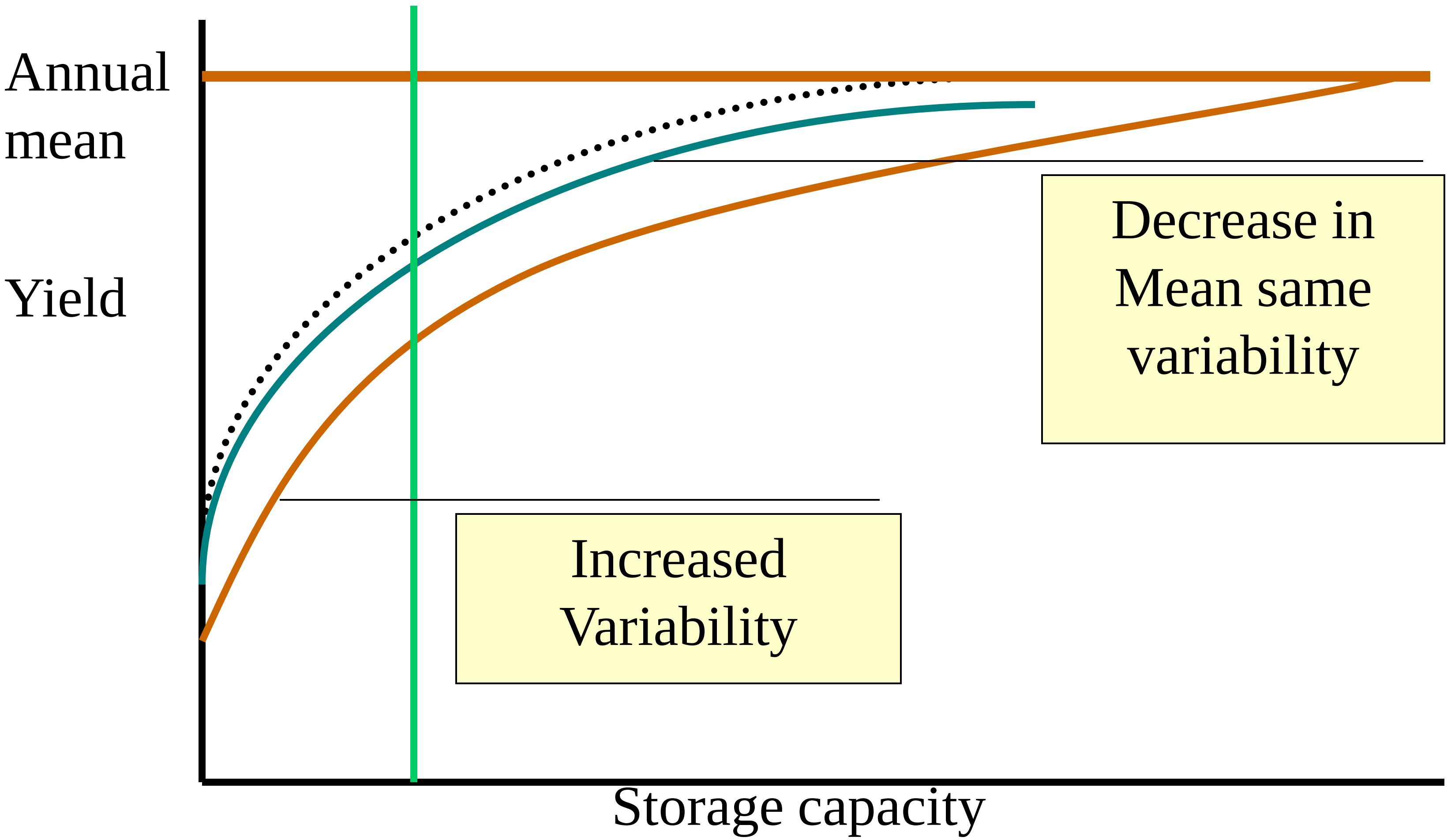




WATER MANAGEMENT

- Bring Water to Where it is needed when it is needed
- Great Environmental Costs
- Market Benefit
- Social Costs and Benefits

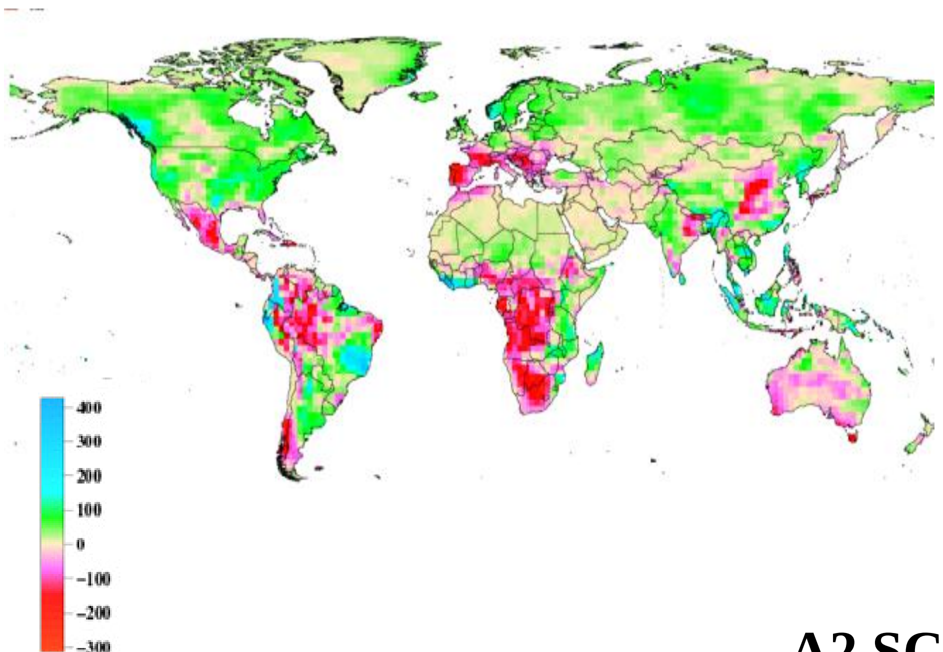
Storage Yield Curves

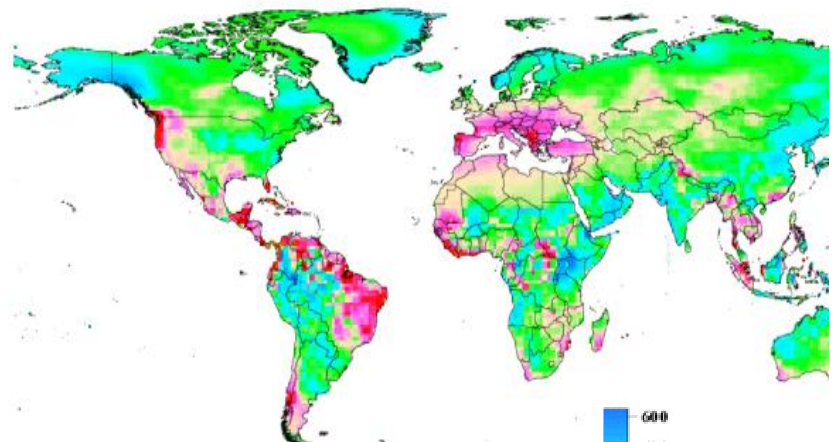


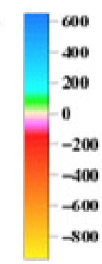
Global Wet and Dry

Change in average annual precipitation, 2000 – 2050

CSIRO (DRY) **NCAR (WET)**



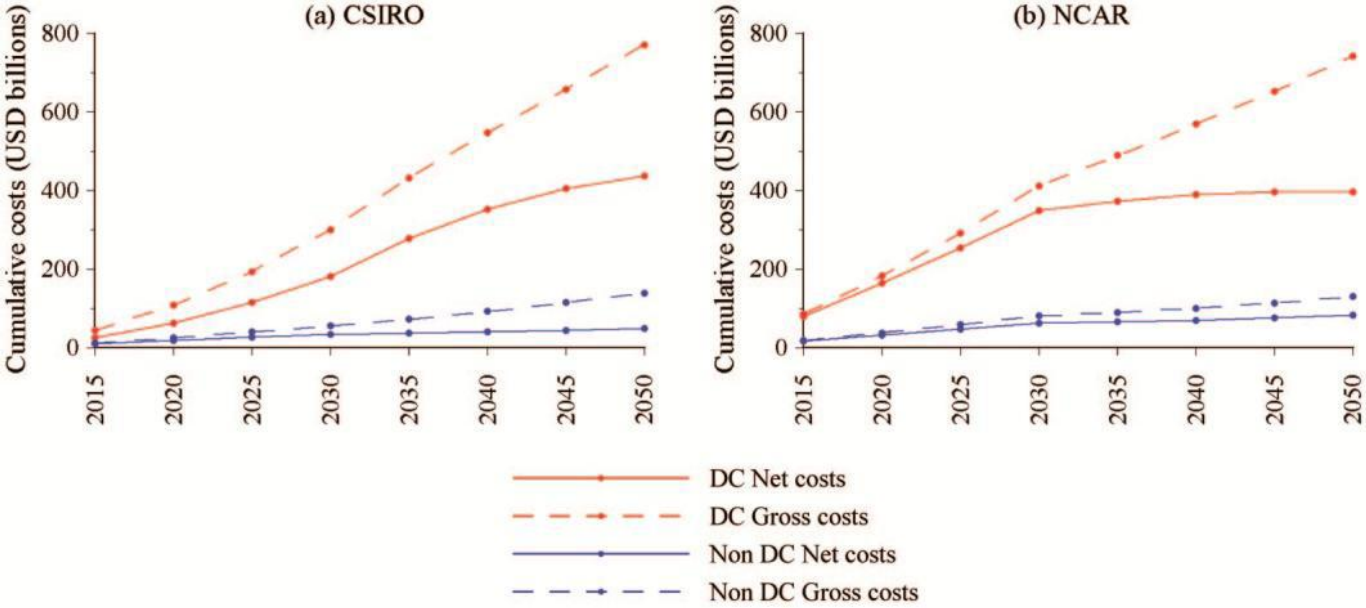




A2 SCENARIO

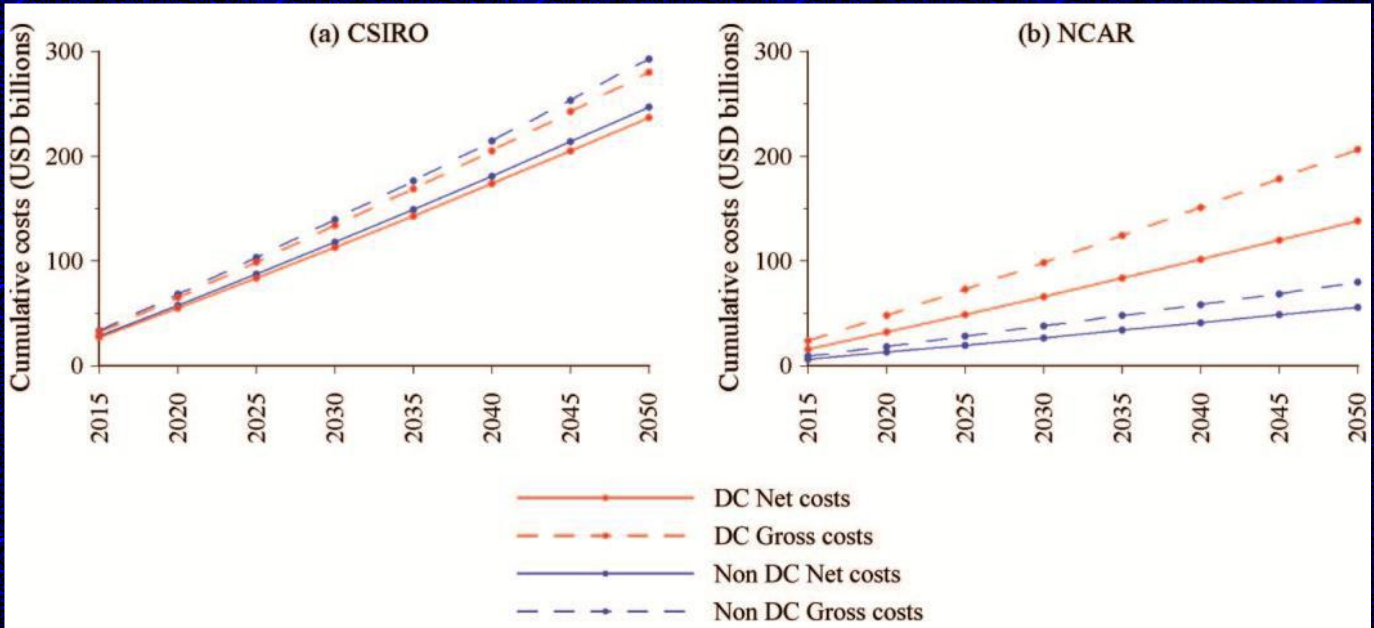
Two extreme GCMs used to estimate range of costs

Cost of Adaptation in 2050 (Ward et 2010)

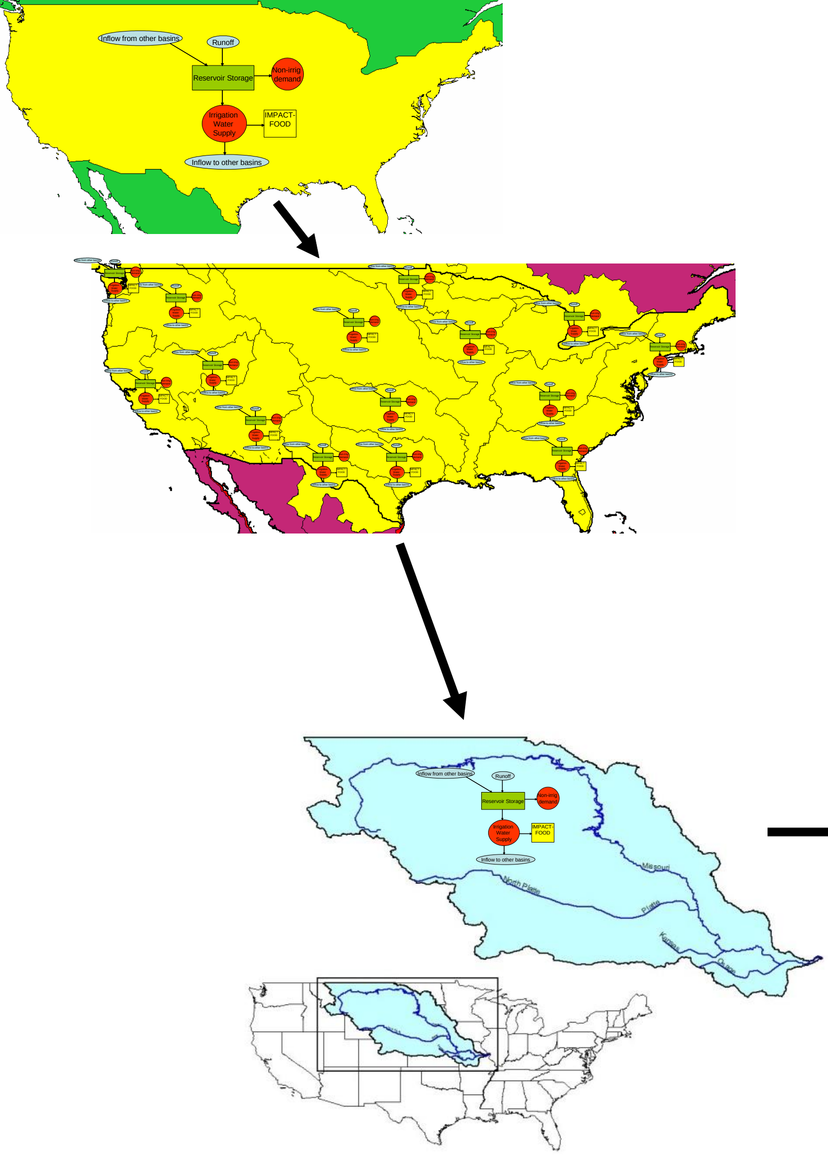


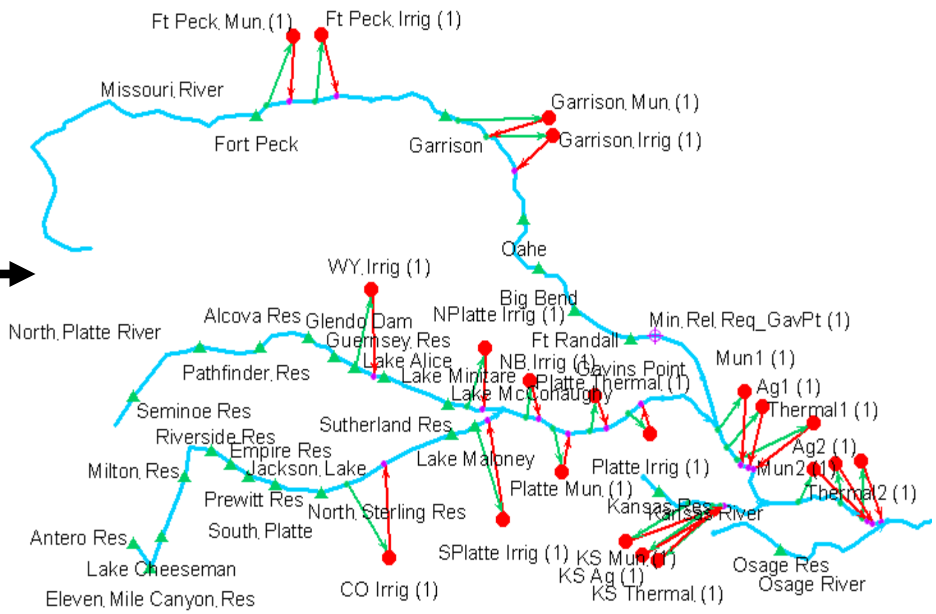
Water Supply

Flooding

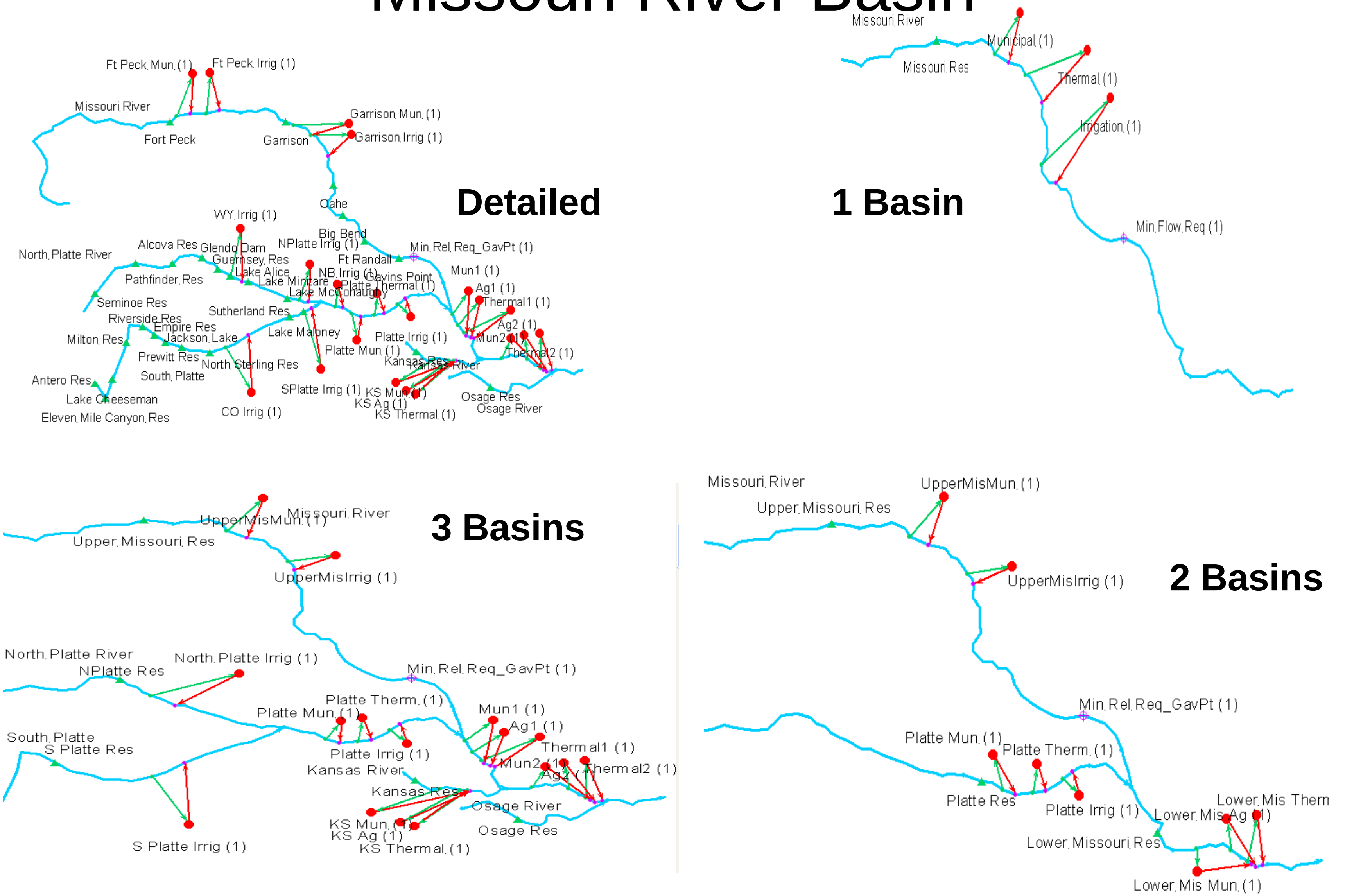


“What is the importance of spatial scale and management on river basin modeling for global food production?”

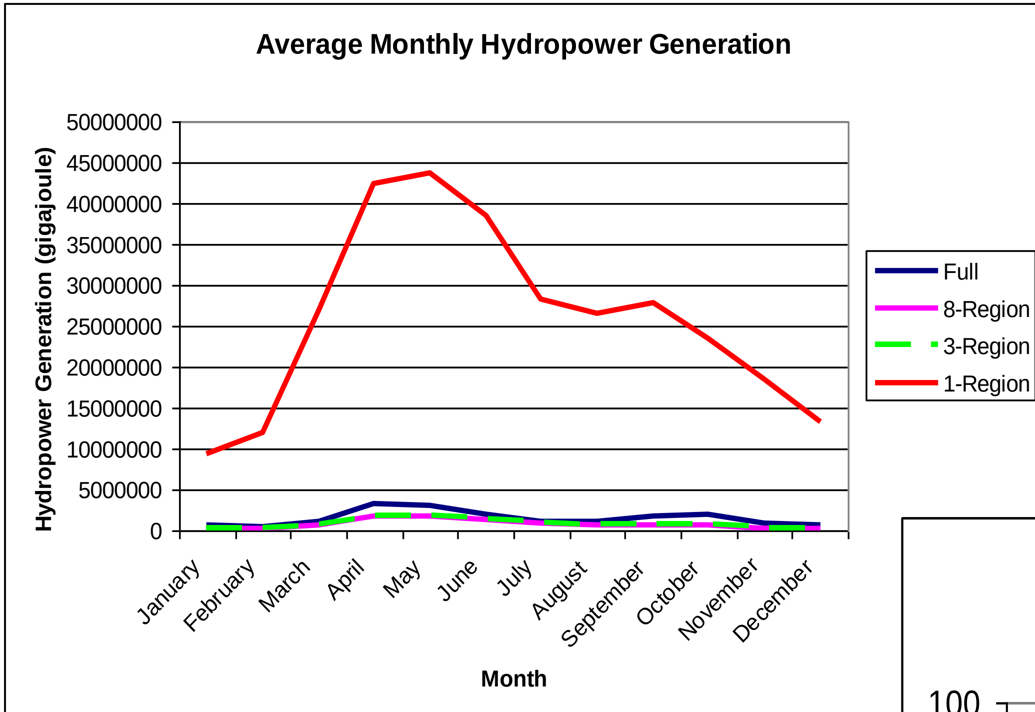


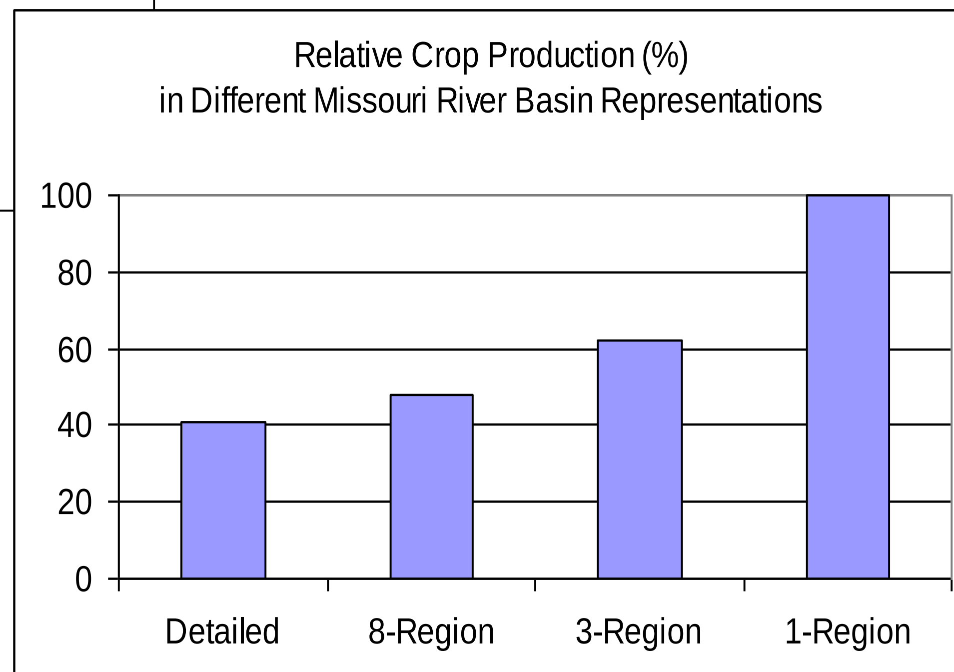


4 Spatial Scale Representations of Missouri River Basin

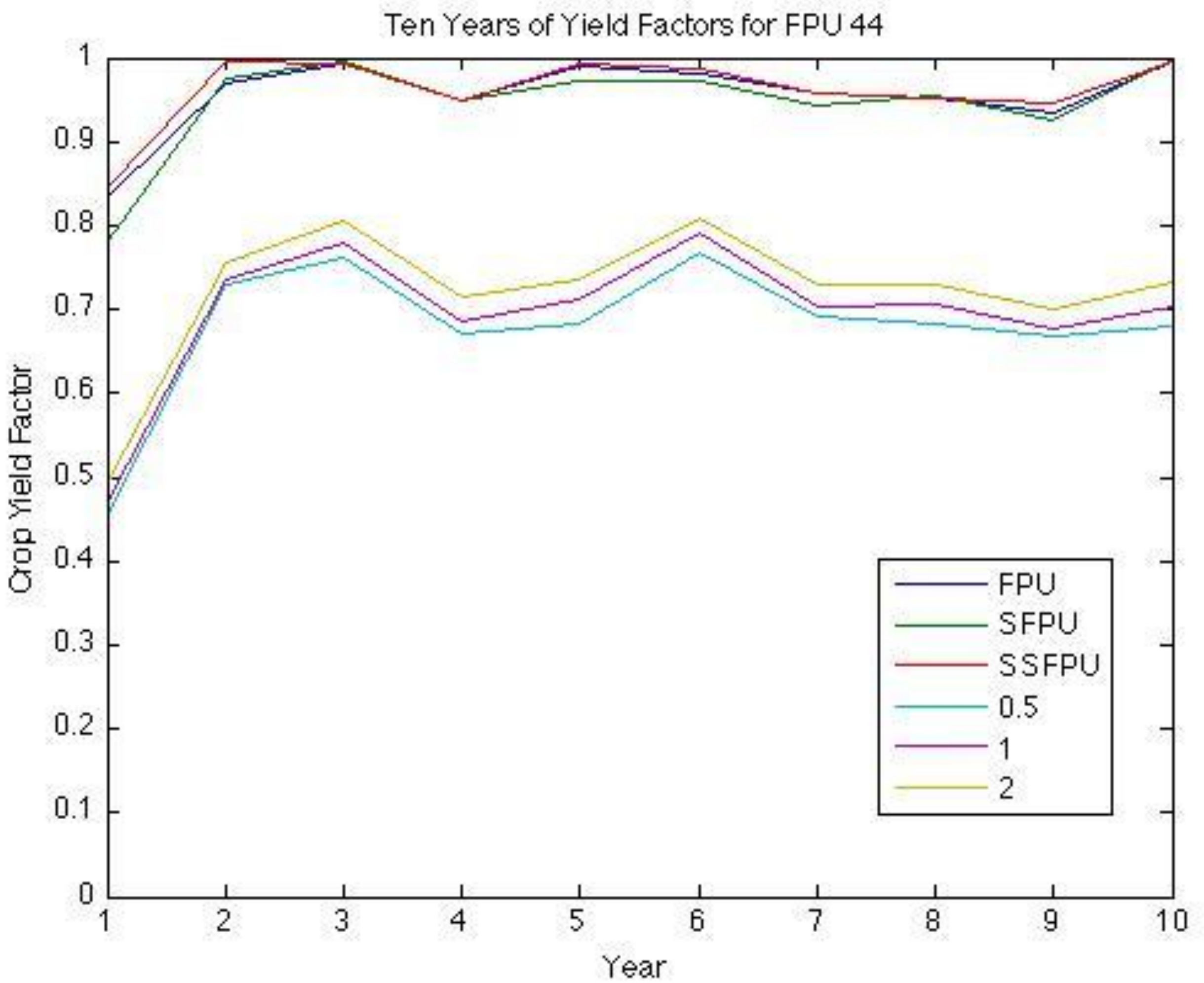


Average Monthly Hydropower Generation in each of the Missouri River Spatial Representations

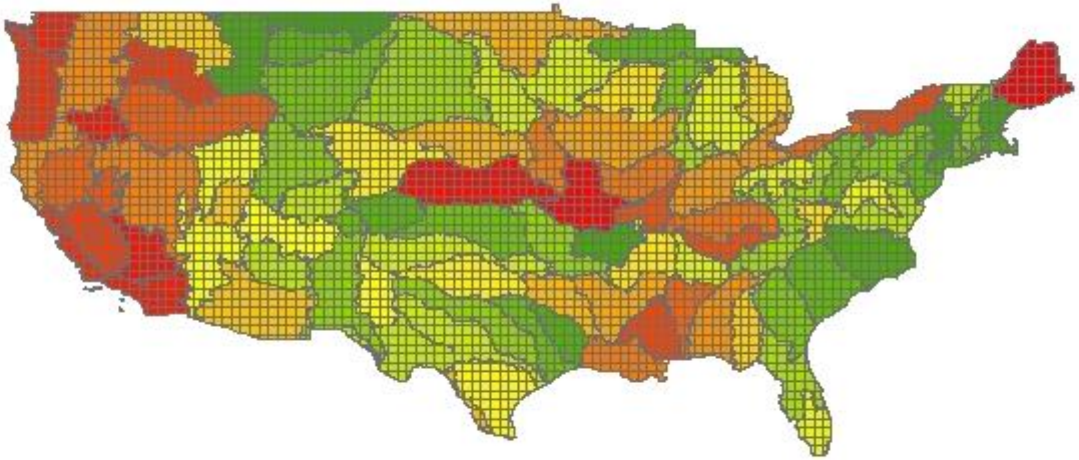




Spatial Resolution Impacts on Estimated Crop Water Stress (Farmer et al, 2010)

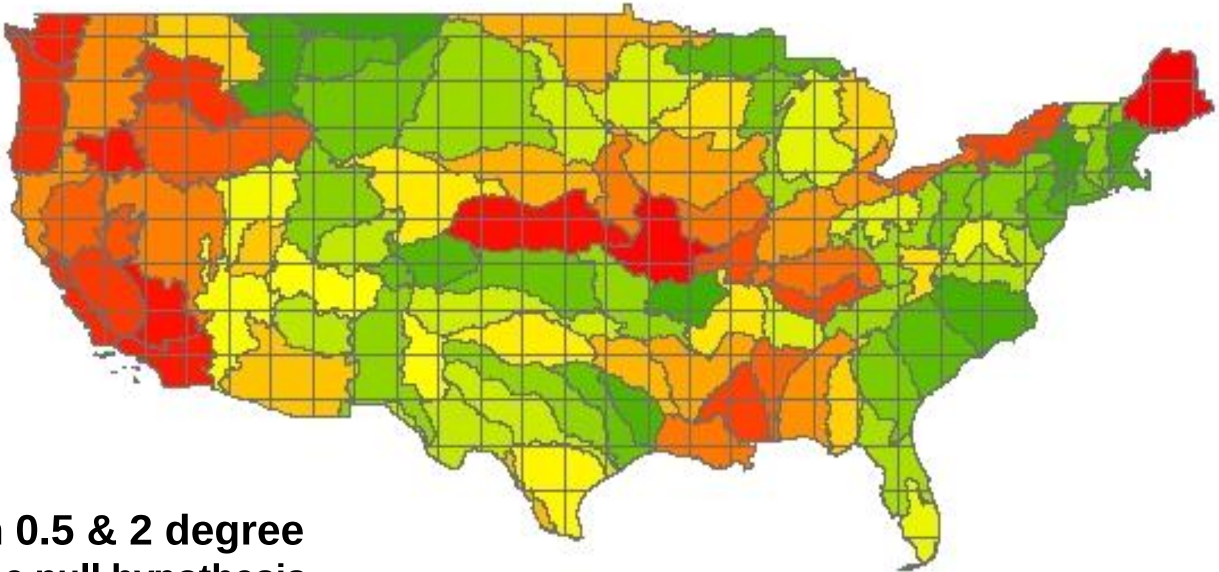


Spatial Unit of Crop Modeling (Farmer et al, 2010)



- 0.5 Degree 3000 cells
- 2 degree 180 cells

	0.5	1.0	2.0
0.5	1.0	0.80	0.08
1.0		1.0	0.13
2.0			1.0

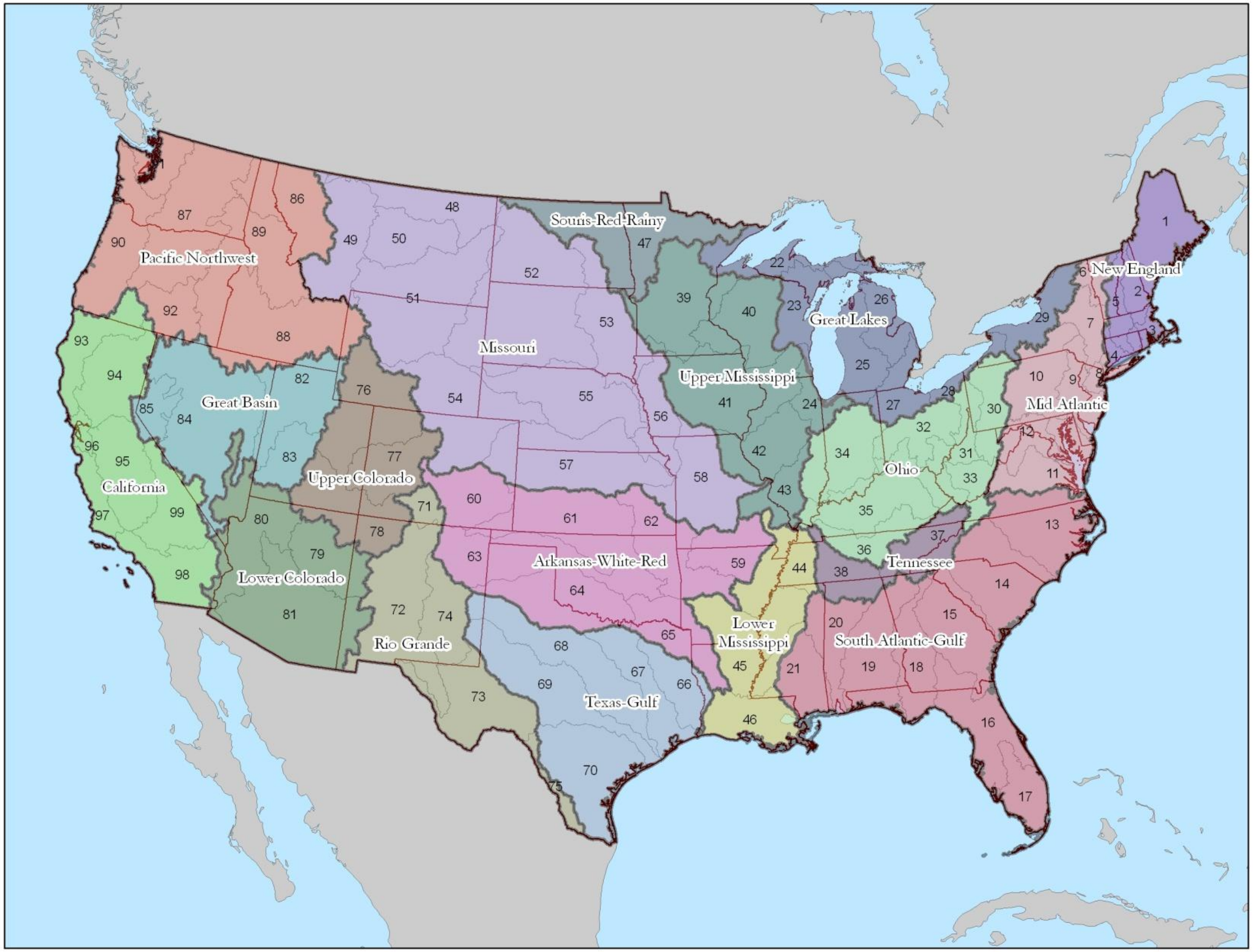


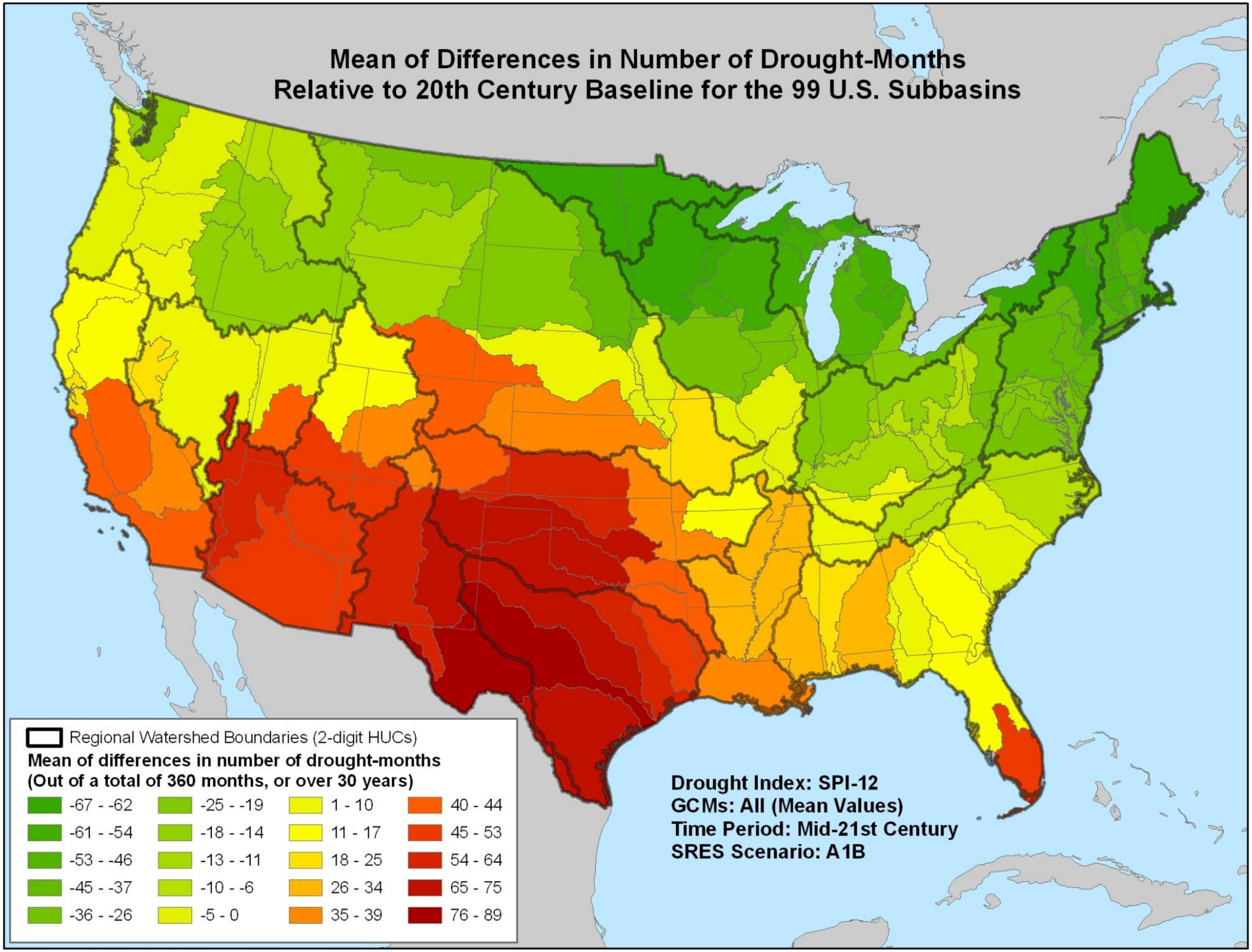
No Statistical Difference between 0.5 & 2 degree

A p-value less than 0.05 will reject the null hypothesis.

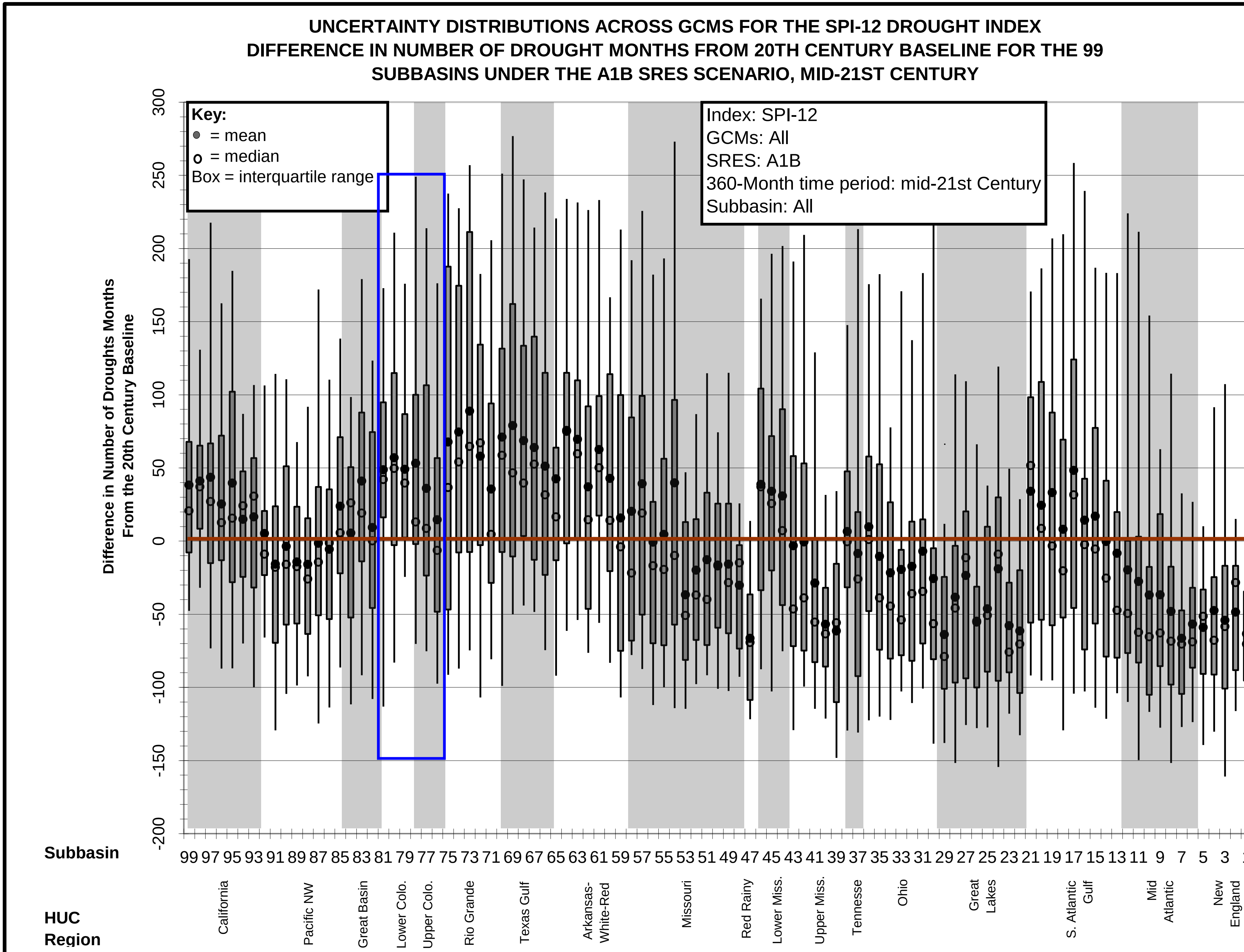
River Basin Spatial Scale for USA
30 to 99[1] basins

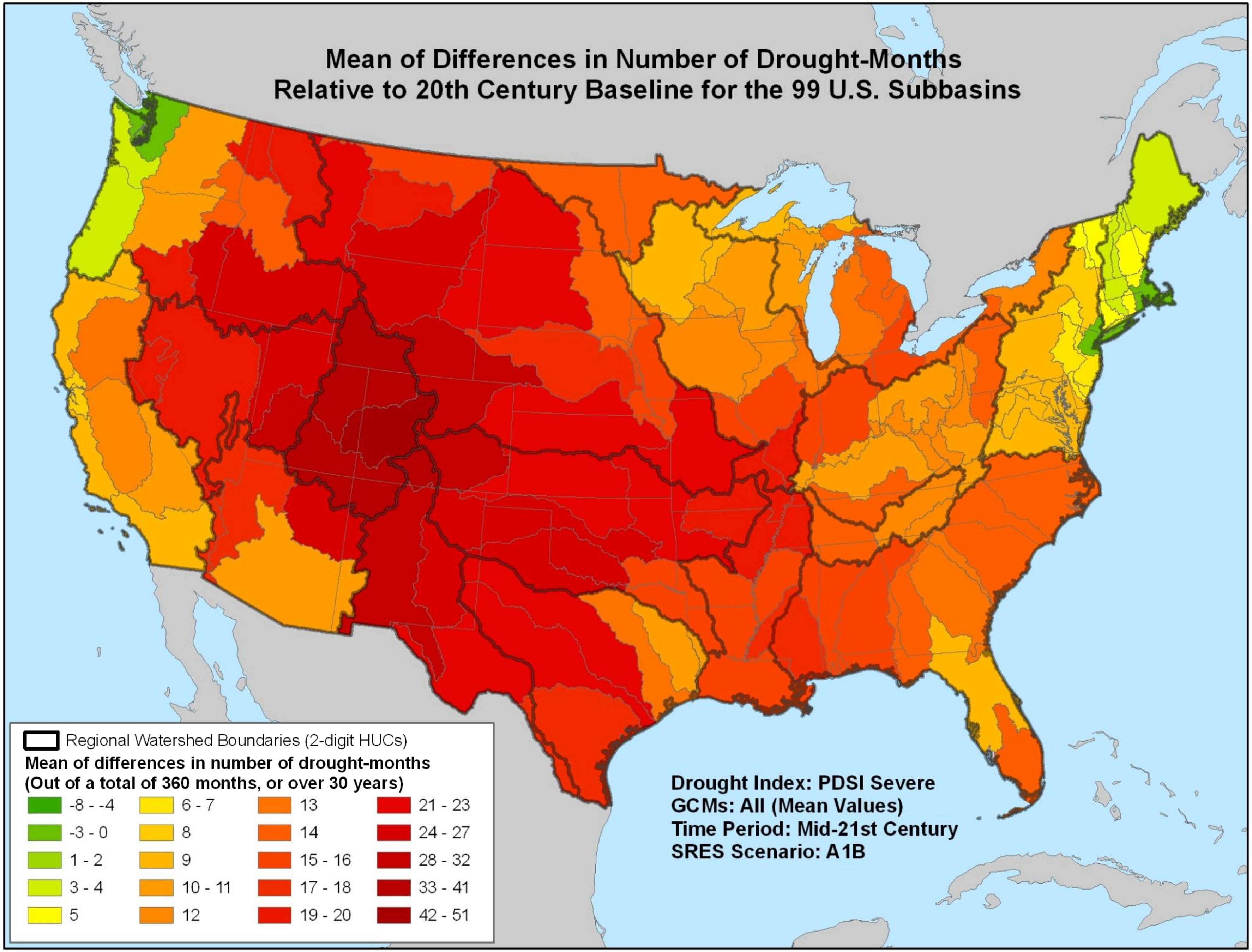
[1] Source: Subbasin Assessment Regions 1978 Water Resources Council, 2nd National Assessment

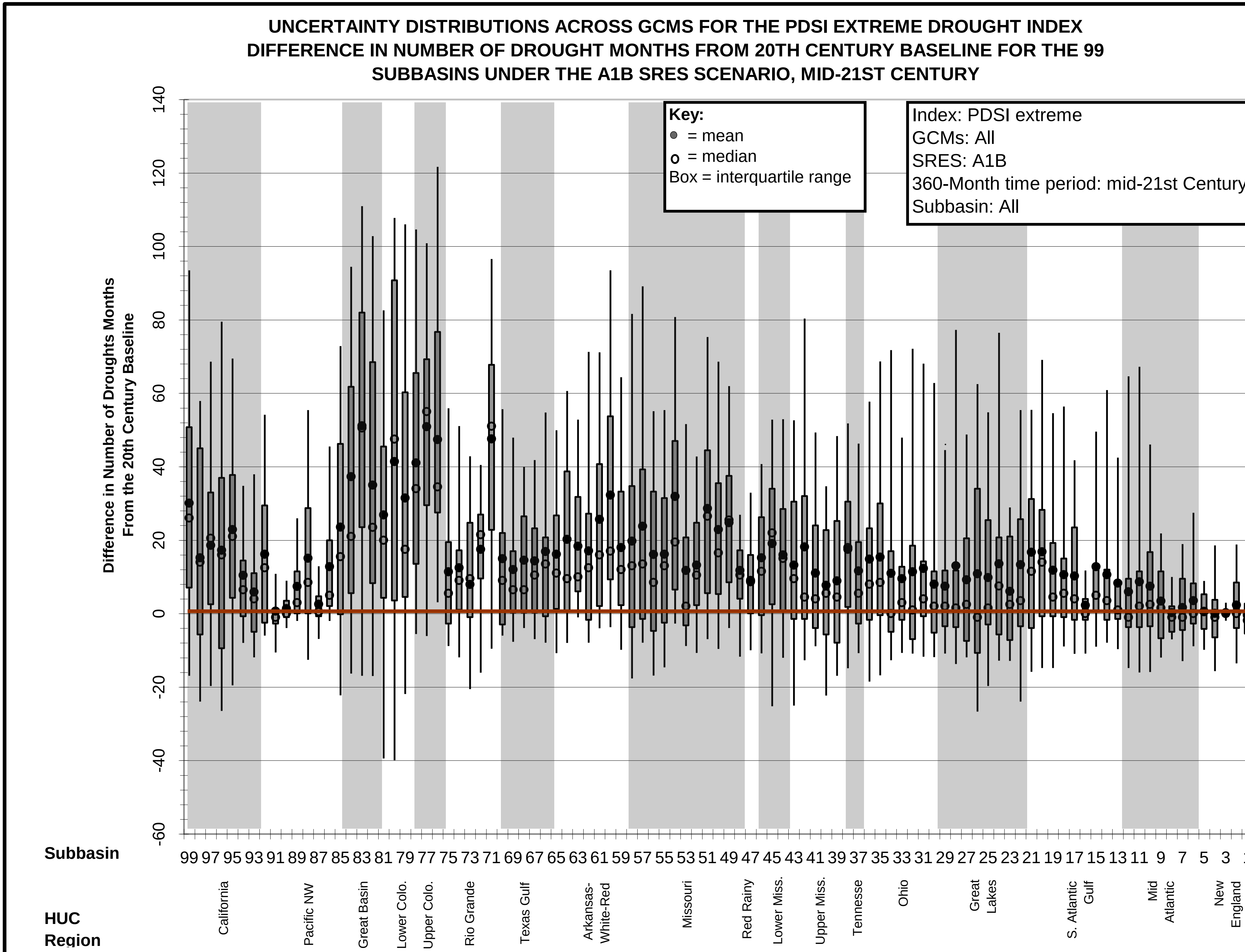




Mean of Differences in Number of Drought-Months
Relative to 20th Century Baseline for the 99 U.S. Subbasins
Regional Watershed Boundaries (2-digit HUCs)
Mean of differences in number of drought-months
(Out of a total of 360 months, or over 30 years)
-67 - -62
-61 - -54
-53 - -46
-45 - -37
-36 - -26
-25 - -19
-18 - -14
-13 - -11
-10 - -6
-5 - 0
1 - 10
11 - 17
18 - 25
26 - 34
35 - 39
40 - 44
45 - 53
54 - 64
65 - 75
76 - 89
Drought Index: SPI-12
GCMs: All (Mean Values)
Time Period: Mid-21st Century
SRES Scenario: A1B

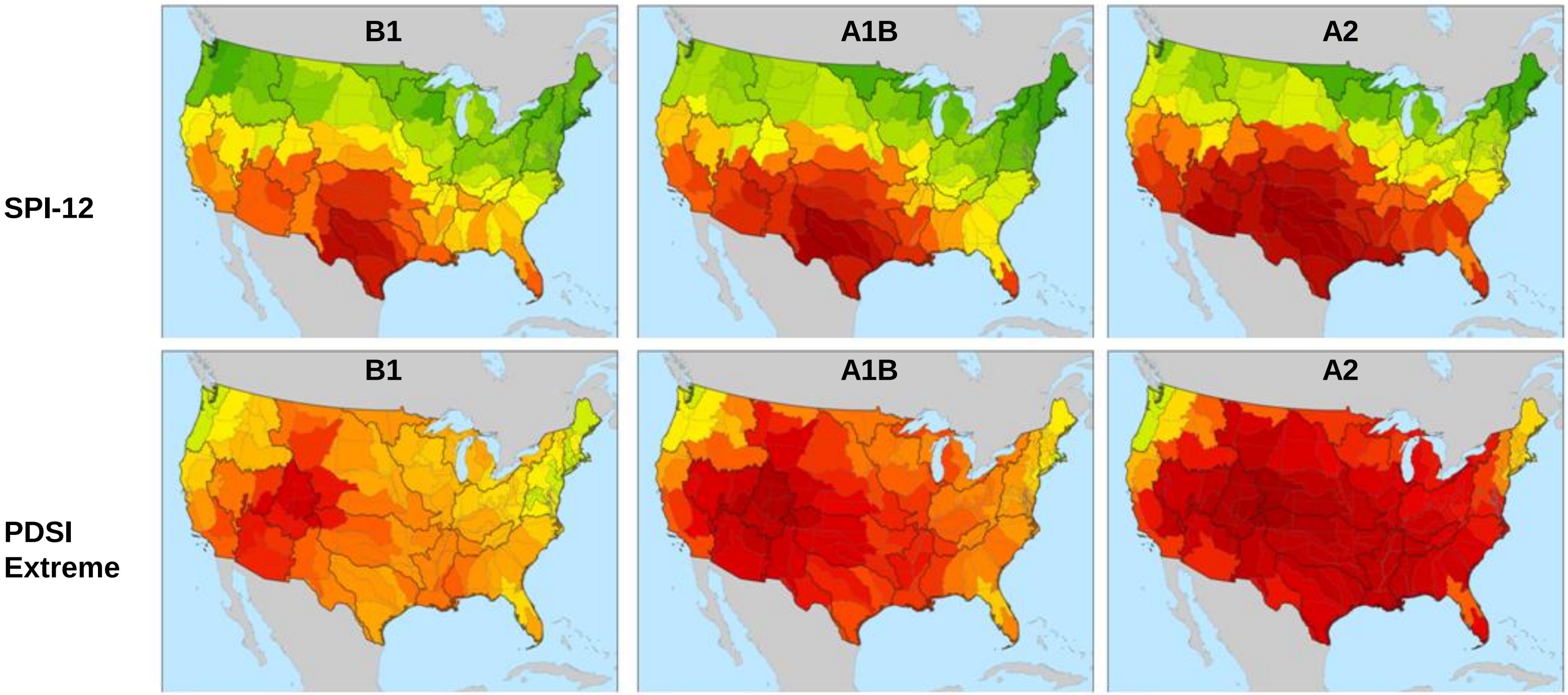

UNCERTAINTY DISTRIBUTIONS ACROSS GCMS FOR THE SPI-12 DROUGHT INDEX
DIFFERENCE IN NUMBER OF DROUGHT MONTHS FROM 20TH CENTURY BASELINE FOR THE 99
SUBBASINS UNDER THE A1B SRES SCENARIO, MID-21ST CENTURY
Key:
= mean
= median
Box = interquartile range
Index: SPI-12
GCMs: All
SRES: A1B
360-Month time period: mid-21st Century
Subbasin: All
Difference in Number of Droughts Months
From the 20th Century Baseline
300
250
200
150
100
50
0
-50
-100
-150
-200
Subbasin
99 97 95 93 91 89 87 85 83 81 79 77 75 73 71 69 67 65 63 61 59 57 55 53 51 49 47 45 43 41 39 37 35 33 31 29 27 25 23 21 19 17 15 13 11 9 7 5 3 1
HUC
Region
California
Pacific NW
Great Basin
Lower Colo.
Upper Colo.
Rio Grande
Texas Gulf
Arkansas-
White-Red
Missouri
Red Rainy
Lower Miss.
Upper Miss.
Tennessee
Ohio
Great
Lakes
S. Atlantic
Gulf
Mid
Atlantic
New
England


Mean of Differences in Number of Drought-Months
Relative to 20th Century Baseline for the 99 U.S. Subbasins
Regional Watershed Boundaries (2-digit HUCs)
Mean of differences in number of drought-months
(Out of a total of 360 months, or over 30 years)
-8 - -4
-3 - 0
1 - 2
3 - 4
5
6 - 7
8
9
10 - 11
12
13
14
15 - 16
17 - 18
19 - 20
21 - 23
24 - 27
28 - 32
33 - 41
42 - 51
Drought Index: PDSI Severe
GCMs: All (Mean Values)
Time Period: Mid-21st Century
SRES Scenario: A1B

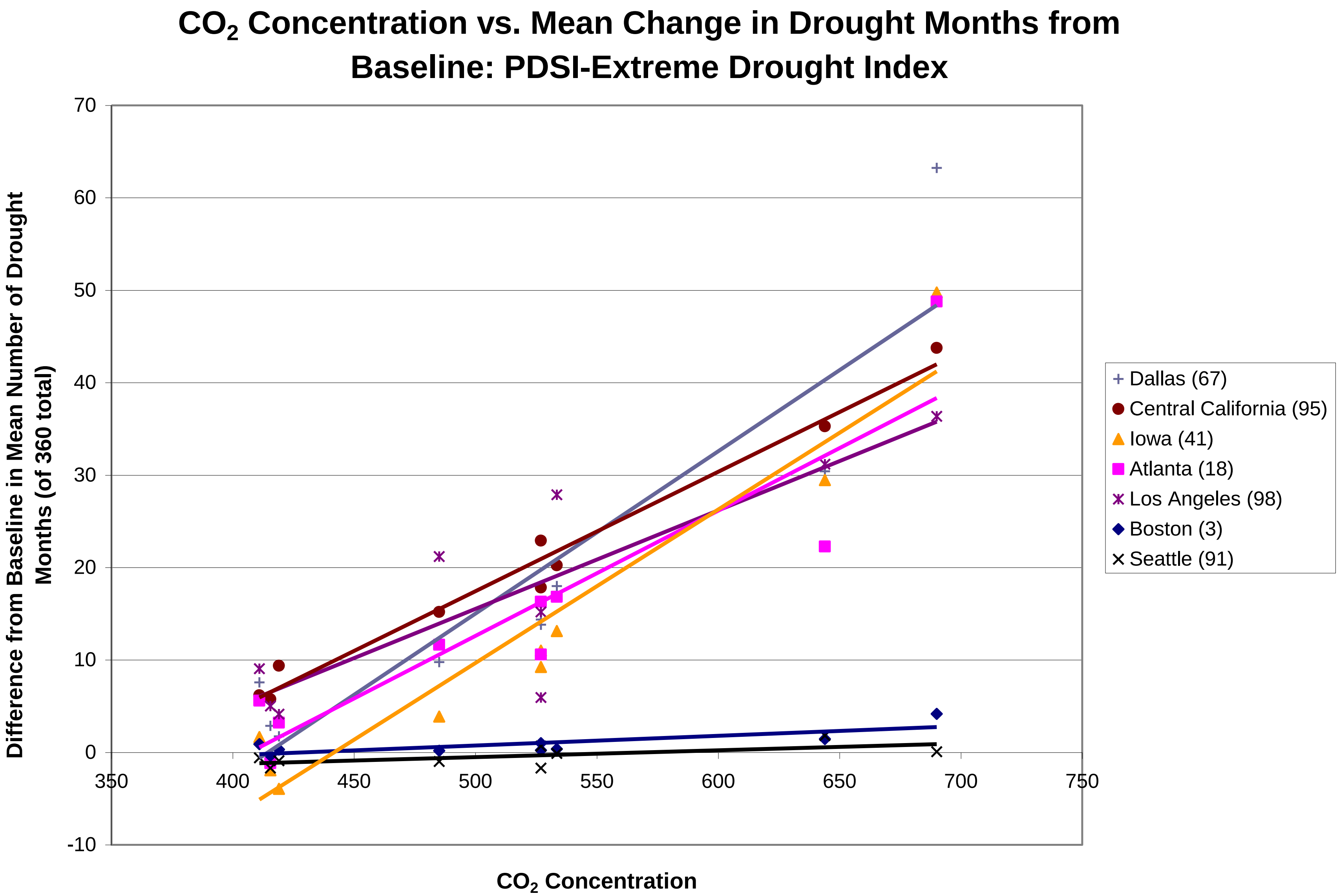

UNCERTAINTY DISTRIBUTIONS ACROSS GCMS FOR THE PDSI EXTREME DROUGHT INDEX
DIFFERENCE IN NUMBER OF DROUGHT MONTHS FROM 20TH CENTURY BASELINE FOR THE 99
SUBBASINS UNDER THE A1B SRES SCENARIO, MID-21ST CENTURY
Key:
= mean
= median
Box = interquartile range
Index: PDSI extreme
GCMs: All
SRES: A1B
360-Month time period: mid-21st Century
Subbasin: All
Difference in Number of Droughts Months
From the 20th Century Baseline
140
120
100
80
60
40
20
0
-20
-40
-60
Subbasin
99 97 95 93 91 89 87 85 83 81 79 77 75 73 71 69 67 65 63 61 59 57 55 53 51 49 47 45 43 41 39 37 35 33 31 29 27 25 23 21 19 17 15 13 11 9 7 5 3 1
HUC
Region
California
Pacific NW
Great Basin
Lower Colo.
Upper Colo.
Rio Grande
Texas Gulf
Arkansas-White-Red
Missouri
Red Rainy
Lower Miss.
Upper Miss.
Tennessee
Ohio
Great Lakes
S. Atlantic Gulf
Mid Atlantic
New England

Mean Changes in Drought Index Values from Baseline

B1, A1B, and A2 SRES Scenarios in Late 21st Century (Strzepek et al 2010)

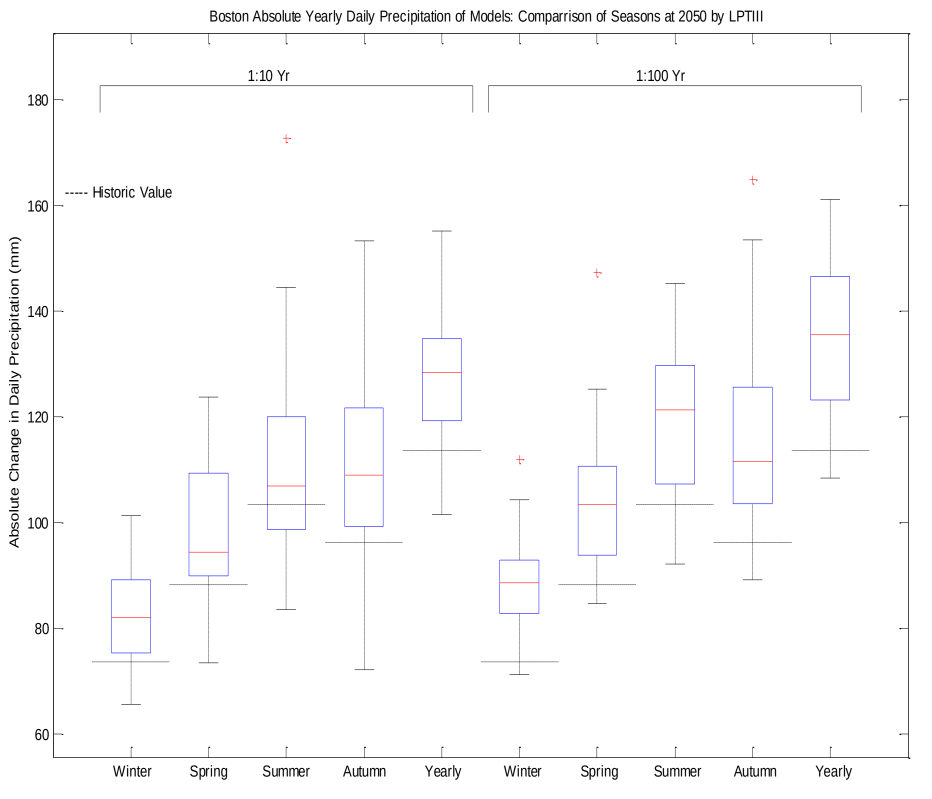


Observation 4b: Emissions have a more pronounced effect on droughts when both temperature and precipitation are considered.



Boston Design Storm 2050

Current Uncertainty in 100 yr Storm much greater than range of GCM Changes



CC Impacts on Roadway Bridges USEPA by Stratus

Table 13. Number of currently deficient bridges per 2-digit HUC vulnerable to climate change for the historical 100-year, 24-hour storm. This includes currently deficient bridges with a projected increase in modeled flow of more than 20% for three future emissions scenarios (A2, A1B, B1) and two time periods (2055, 2090).

HUC	A2 2055	A1B 2055	B1 2055	A2 2090	A1B 2090	B1 2090
1	2,430	3,026	1,428	2,904	2,717	2,726
2	7,395	3,871	3,409	8,734	8,100	4,749
3	15,106	7,772	6,860	23,072	19,552	3,987
4	4,556	3,675	4,482	4,975	5,198	4,629
5	11,996	8,458	6,350	12,654	12,870	10,156
6	2,875	3,105	3,677	4,306	4,306	2,980
7	7,246	6,030	5,591	8,129	8,405	4,354
8	6,114	541	1,404	11,761	4,669	1,325
9	351	221	343	351	356	325
10	11,722	8,205	6,539	10,329	12,453	9,979
11	5,774	1,648	925	6,516	5,481	4,612
12	6,254	1,783	1,440	7,433	5,300	9,617
13	453	426	291	528	515	538
14	502	274	250	400	405	486
15	773	285	123	752	493	301
16	545	360	463	515	545	534
17	4,665	2,675	1,666	5,545	3,688	3,011
18	2,357	459	2,087	2,530	2,551	496
Total	91,114	52,814	47,328	111,434	97,604	64,805

Impacts on Roadway Bridges

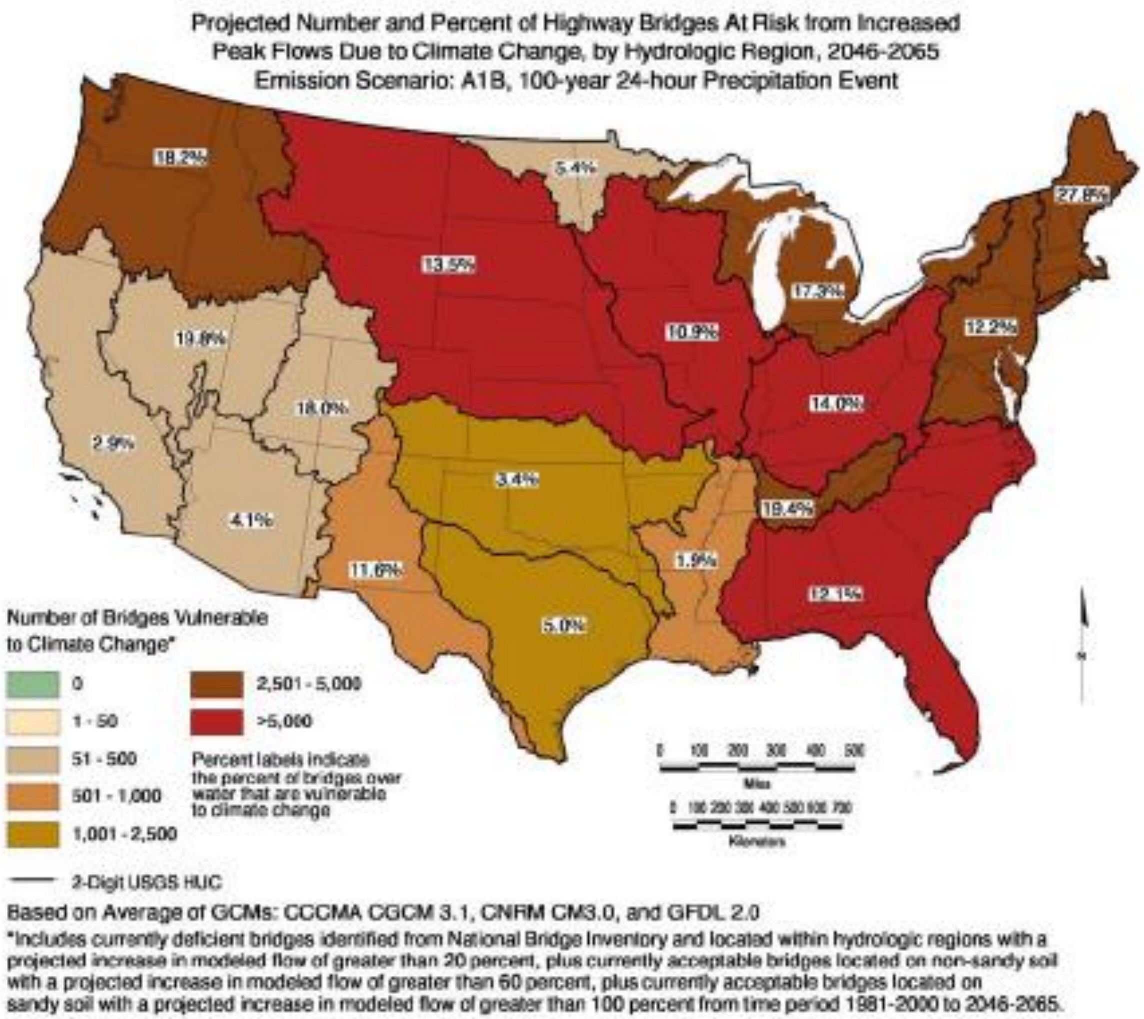
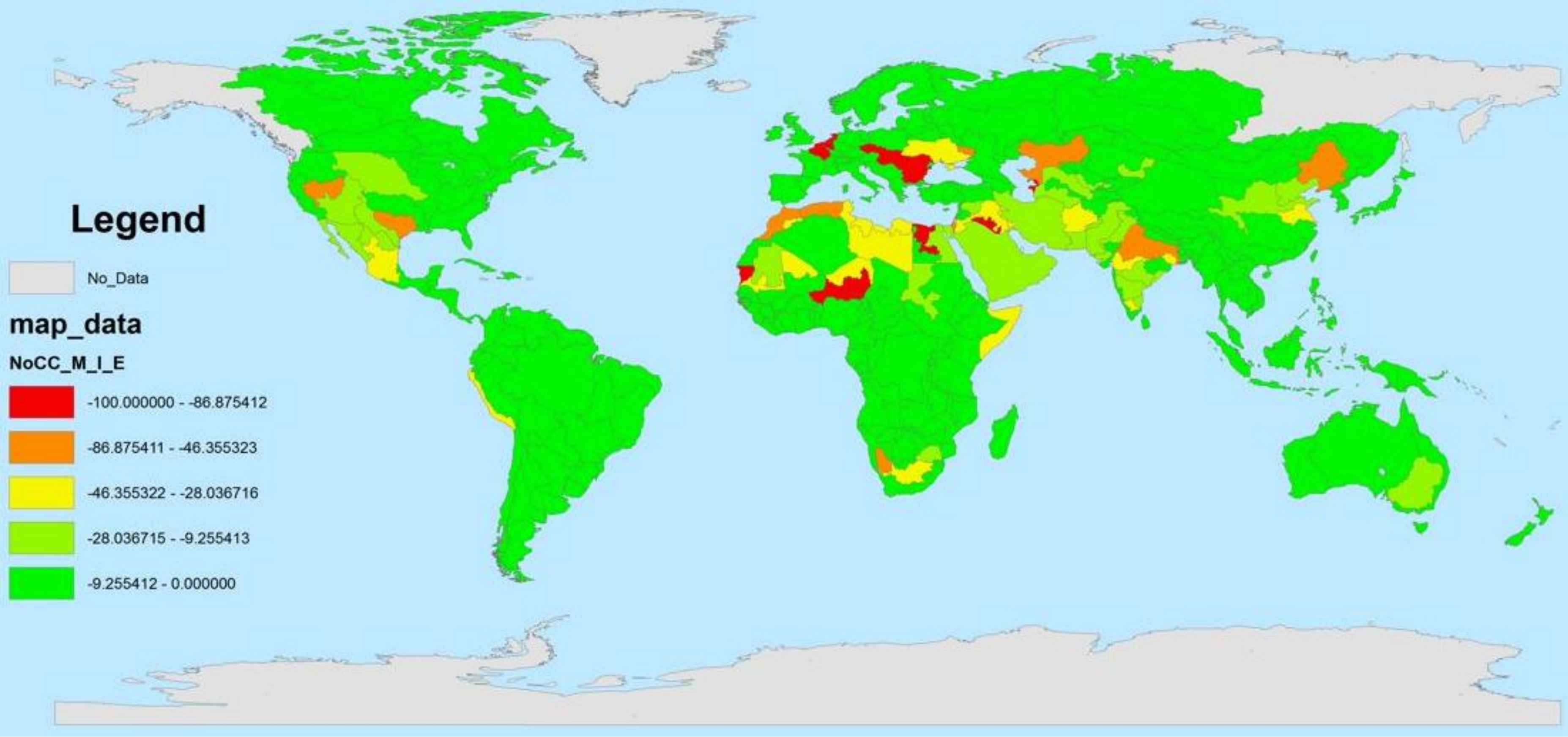


Figure 10. 2046–2065, 100-year, 24-hour storm, Scenario A1B.

Threats to Existing Ag Water (Strzepek & Boehlert, 2010)



Threats to Existing Ag Water

Foresight Region	2000 Agricultural Withdrawals (billion m^3)	No Climate Change		
		2050 M&I	EFRs	2050 M&I and EFRs
World	**2,946**	**7.3%**	**9.4%**	**17.7%**
Europe	**263**	**2.5%**	**7.7%**	**14.4%**
European Union	95	0.7%	12.8%	18.7%
Northwestern Europe	16	4.5%	11.7%	8.2%
United Kingdom	0.6	0.0%	0.0%	0.0%
Former Soviet Union	186	3.2%	10.0%	19.7%
Africa	**246**	**9.8%**	**5.8%**	**15.8%**
Sub-Saharan Africa	50	11.9%	7.2%	16.4%
Nile River Basin	146	9.1%	0.2%	9.2%
North America	**255**	**-0.1%**	**15.2%**	**14.9%**
Asia	**2,060**	**8.8%**	**8.9%**	**18.6%**
China	558	2.7%	7.3%	10.1%
India	866	13.5%	12.1%	27.7%
Latin America and the Caribbean	**182**	**3.8%**	**12.3%**	**16.1%**
Brazil	21	0.0%	0.0%	0.0%
Oceania	**50**	**0.2%**	**14.3%**	**14.5%**

Climate Change Threats to Ag Water

	Historic	WET	DRY
World	17.7	16.5	16.9
Europe	14.4	12.9	20.4
Africa	15.8	16.9	17.1
N.America	14.9	13.6	12
Asia	18.6	16.7	16.8
Latin Amer	16.1	19.9	16.8
Oceania	14.5	14.5	14.5

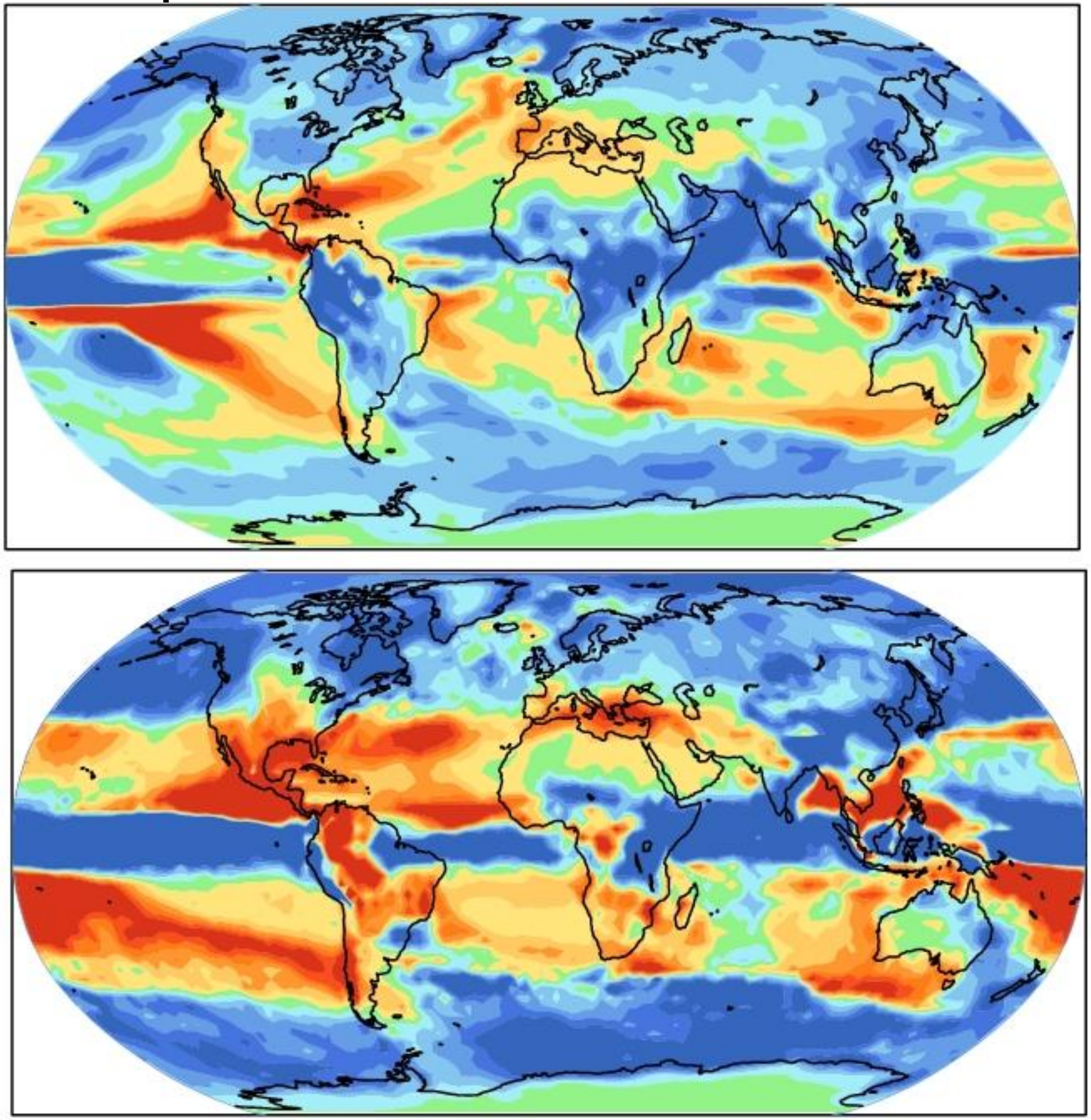
Water For Environment versus AG - Happening

- **Australian farmers are furious about a government concession to nature Australia's water war**
- AFTER a ten-year drought, farmers along the Murrumbidgee River now face ruin from a devastating flood. But it is the government that riles them as much as any caprice of nature. Last month officials called for a cut of nearly 40% in the volume of river water they take for irrigation. At a rowdy meeting in Narrandera, a river town, John Bonetti, a third-generation farmer, drew cheers from about 900 farmers when he told visiting bureaucrats and scientists, “If you think this is the end of the fight, I can assure you it’s only the bloody start.”

Summary

- SCALE MATTERS
- Cannot sum water impacts across sectors for Impacts and especially Adaptation must model Basin Scale Water Mgt Systems (Smith, Hurd next talk)
- FLOODING VERY IMPORTANT
  - Need “additional” information from GCMs
- CLIMATE CHANGE IN THE CONTEXT OF GLOBAL CHANGE

Precipitation 2100: CCSM v. MIROC



CC Impacts on Roadway Bridges

Stratus Consulting (Final, 8/12/2010)

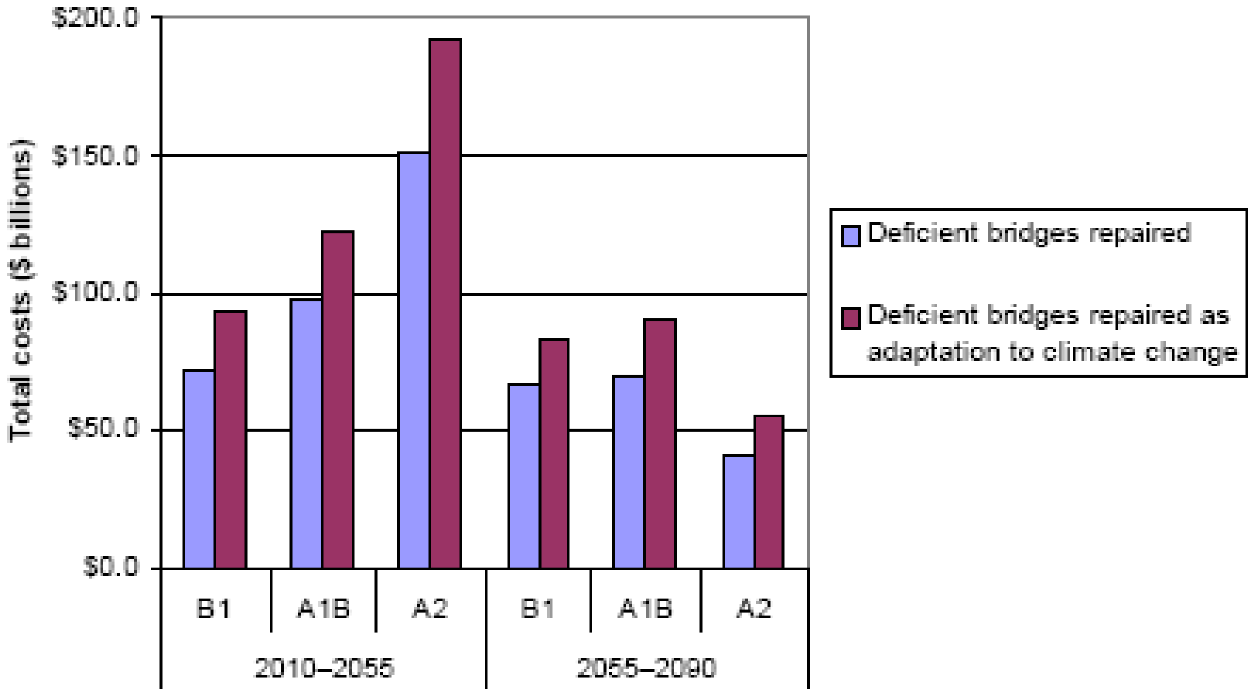
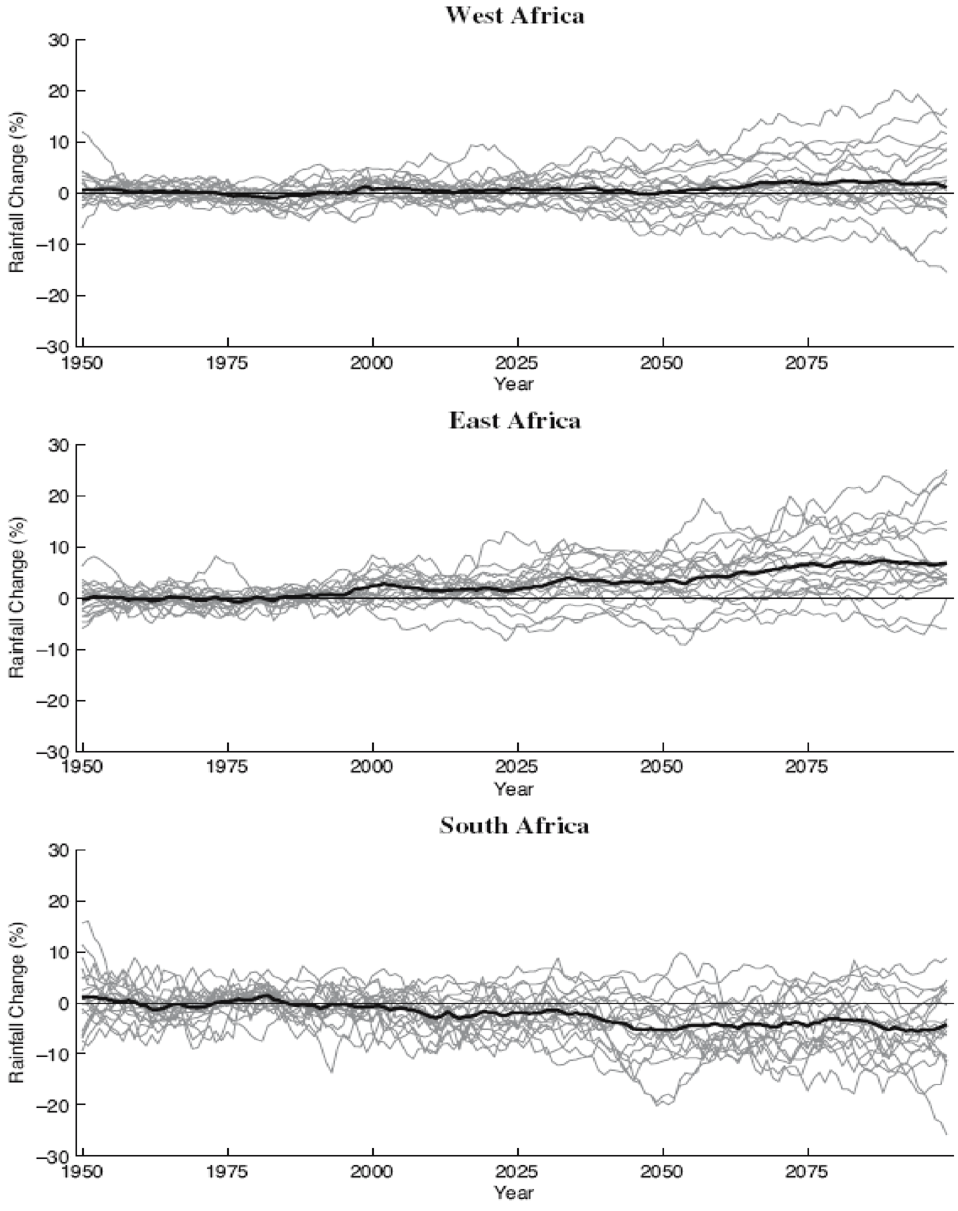


Figure 16. Costs for adapting deficient bridges to climate change by time period and scenario.

IPCC AR4 Precipitation



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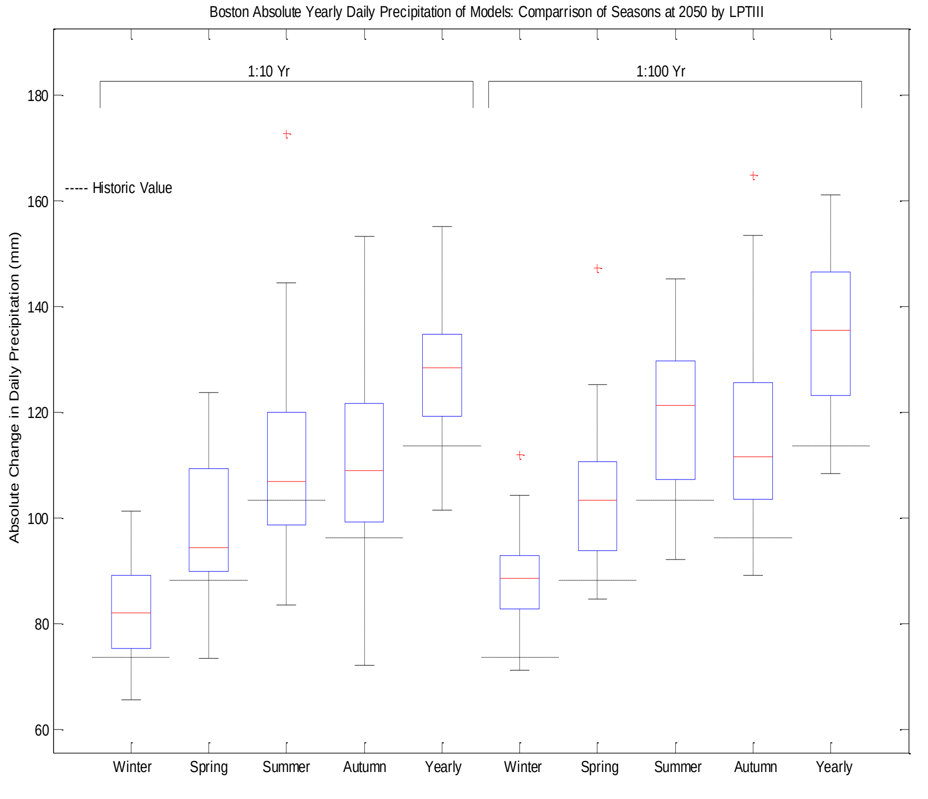
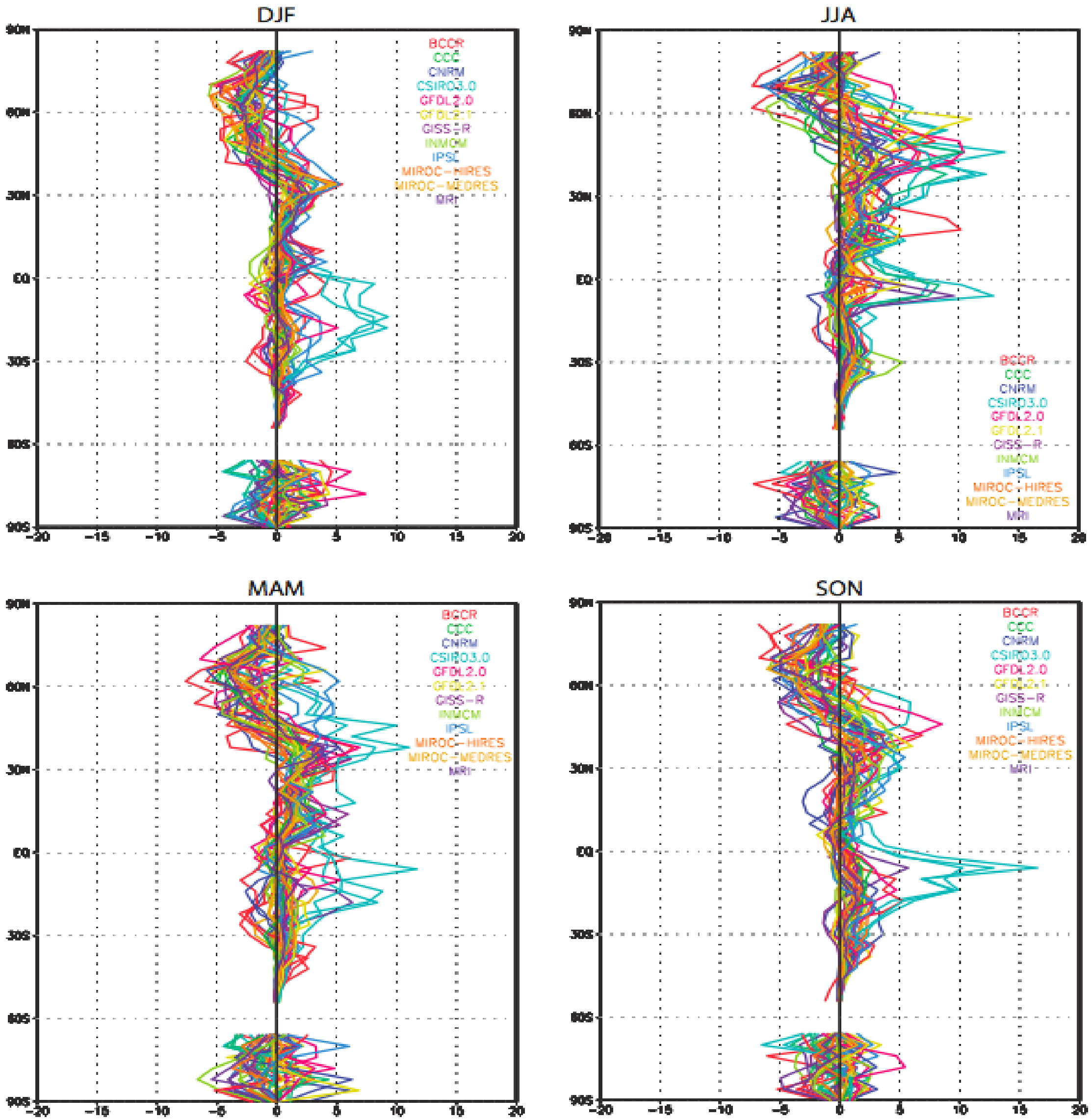


Change in Precipitation Event Interval (%/°C)



Brief Summary of Studies that Estimate the Economic Impact of Changes in Climate and Water Availability

Brian H. Hurd and Mani Rouhi-Rad (New Mexico State University, bhurd@nmsu.edu)

Jan 24, 2011

1. Overview

As is well known, water management infrastructures and institutions have evolved to help communities cope with a moderate range of water supply variability and uncertainty. With few exceptions, U.S. communities, industries and water users regardless of their location have evolved capacities to sustain successfully within the context of their local water supply fluctuations and climate variability that is with a variability that is within their 'norm'. Mild fluctuations, moderate variability, even occasional extremes are typically within the normal realm of expectation. Resilience is a characteristic of communities, industries, organizations, and residents that are moderately to well prepared and capable of responding well to 'occasional' extremes. (Figure 1 from the USGS shows water use patterns across the U.S.) However, as the accumulation of science indicates the climate forcing of anthropogenic greenhouse gas emissions is highly likely to contribute to climate uncertainty (e.g., Parry et al., IPCC FAR, 2007 and others). And if this uncertainty can be expected to lead to more frequent, persistent and intense deviations beyond the prevailing capacities of water users to cope, then the risks and consequences facing water users within communities, industries, and organizations become an economic concern.

Both human and natural systems are vulnerable to such changes, and to their conflation with other significant stressors like population growth, loss of habitat and biodiversity, resource scarcity etc. Water systems are particularly sensitive to climatic changes. Both surface- and ground-water supplies can be affected by extreme or persistent changes in the amount and timing of precipitation, temperature driven processes such as evaporation and vegetative evapotranspiration, snowmelt, vegetation cover, and streamflow patterns. Water users are also directly and indirectly affected by extreme and or persistent changes in climate, for example, as rising temperatures increase consumptive irrigation requirements for many crops including irrigated lawns and gardens. And in municipal water systems an increase in seasonal temperatures would likely be experienced as an increase in the effective length of 'summer' and its inherently higher water demands as well as greater 'peak' demands and the associated strain on water delivery capacity and infrastructure.

In this brief abstract, we survey the literature on economic impacts to water systems and resources, with a focus on national and region-wide estimates and on the most recent studies where they have been conducted. There are far more studies linking climate change and hydrology than those considering economic endpoints. In fact there are surprisingly few studies that complete the linkages between climate change, water and economic consequences. We have tried to access and include as many as we could identify.

2. National Scale Estimates

Examining climate change impacts on water resources on a national scale is quite daunting and there are few examples to draw upon. This is really not at all surprising. There is tremendous variation in water resources and water systems across the U.S. Not only variation across regions but tremendous complexity within regions, and within particular watersheds. Such variation and complexity hinders the development of a comprehensive and consistent assessment of economic impacts on a national basis. Estimation approaches such as large-scale statistical studies that have been used in other sectors such as agriculture (e.g., Mendelsohn et al., 1994) are not well suited with so much uncontrolled variation. Enumerative or aggregation approaches to measuring economic impacts that build a national level estimate by aggregating impacts from each of the nation's watersheds is conceivable in concept but very difficult and costly to execute. Perhaps the closest example of this approach is Hurd et al. (1999a, 2004) where national-level estimates were derived on the basis of only a few large-scale regional estimates and some rather heroic assumptions about the comparability and conformability of some very different regions. Finally, a third way has recently been used to take aim at this difficult problem. Researchers at Sandia National Laboratories have used REMI (Regional Economic Impact, Inc.) in conjunction with a system-dynamics hydrology model and estimated precipitation changes based on the SRES A1B scenario to estimate state-level economic impacts from reduced precipitation.

Research on climate change and its potential economic impacts has steadily evolved from static models based on fixed marginal values to models that capture market dynamics. Early studies by Cline (1992), Fankhauser (1995), and Titus (1992) associated fixed economic values with projections of physical changes (e.g., runoff), with no attempt to account for changes in the marginal value of water or the response of water use to changes in marginal value. Both Cline's (1992) estimated cost of $7 billion and Fankhauser's (1995) estimated cost of $13.7 billion to consumptive water users in the United States are driven by an assumed 10% decrease in water availability. Titus (1992) estimated costs ranging from $21 to $60 billion, including impacts to nonconsumptive users (primarily hydropower and water quality losses), which he observed would most likely exceed the magnitude of impacts to consumptive users.

Hurd, Callaway, Smith and Kirshen (1999a, 2004) approached the problem from a region-specific perspective. Using models of the hydro-economy for four major water resource regions (shown in Figure 2a) and driven by simulated streamflow changes for a set of 15 incremental climate change scenarios, and an extrapolation model based on comparable regions they developed national level estimates of economic damages related to water resources and climate change. They estimated total annual damages to consumptive and non-consumptive water users by as much as $43.1 billion (1994$) under an incremental level of climate change where temperatures rose by 5 deg C and 0 change in precipitation (estimates shown in Figure 2b).

In assessing the potential for climate change to affect water availability on a national scale -- specifically the impacts of reduced precipitation, Sandia National Laboratory (Backus et al., 2010) estimates there is a 50-50 chance that <u>cumulative</u> direct and indirect macro-economic losses in GDP through 2050 will exceed nearly $ 1.1 trillion (2008$), not including flood risks. That is approximately 0.2% of the cumulative GDP projected between 2010 and 2050. They estimate a 50-50 chance of non-discounted annual losses of $60 billion (2008$) by 2050. Their estimation process uses the MIROC3.2 (medium resolution) and the A1B emissions scenario as a motif to guide the assignment of state-level precipitation changes and then uses results from the remaining GCM runs to characterize and assess uncertainty. Water availability changes are assessed at the county-level using Sandia Water Hydrology model. State-level impacts on economic activity changes are analyzed using REMI. [REMI and other input-output type model the changes in economic flows into and out from a region. They <u>do not</u> measure or estimate economic costs and benefits in a theoretically consistent manner. For example, these models do not estimate changes in willingness-to-pay associated with changes in water availability but rather they simulate the economic consequences that are entailed by such changes. For example, in the same way that a disaster can stimulate regional economies as recovery and rebuilding efforts create jobs and raise incomes. In a similar fashion, persistent and severe water shortages can lead to adaptive responses, like building dams and power plants to replace storage and hydropower generation, thus stimulating employment and incomes.

Figure 3 shows the estimated cumulative state-level economic impacts from 2010 through 2050 (green areas show net GDP increases - particularly in California and PNW).

Although there are considerable differences in the above approaches used to estimate national-level annual economic impacts of climate change on water resources, there is a remarkable consistency in the order of magnitude and share of GDP as shown here:

Cline (1992)	$7 billion (~ 0.1% of 1992 US-GDP $6.3 trillion)
Titus (1992)	$21 - 60 billion (~ 0.3 - 0.9% of 1992 US-GDP $6.3 trillion)
Fankhauser (1995)	$13.7 billion (~ 0.2% of 1995 US-GDP $7.4 trillion)
Hurd et al. (1999a, 2004)	$9.4 - 43.1 billion (~ 0.13 - 0.58% of 1995 US-GDP $7.4 trillion)
Backus et al. (SANDIA, 2010)	$ 60 billion (~ 0.4% of 2009 US-GDP $14.1 trillion)

3. Regional Estimates

There are several region-scale estimates. These include the regions underlying the national-estimates of Hurd et al., namely the Colorado River, Missouri Basin, Delaware basin, and Appalachicola-Flint-Chattahoochie in the Southeast, and the state-level assessments provided in the Sandia report (Backus, 2010), as shown in Figure 3. Additional economic studies include California (Lund et al, 2003; Medellin et al., 2006), the Pacific Northwest (Climate Impacts Group, 2009), and the Upper Rio Grande (Hurd and Coonrod, 2007).

California.

Medellin et al. (2006) perform a comprehensive assessment of climate change impacts on California water users. An example of their findings uses the relatively dry GFDL-A2 to estimate a 27% decrease in water availability and with modeled adaptive responses they find "an average annual scarcity of 17%". Water deliveries to agriculture fall by 24% and urban deliveries fall by 1%. They break down the impacts across three categories: scarcity costs, operating costs, and additional policy costs if interregional water transfers are limited. "Of the $360 million/year in average water scarcity costs for 2050 with dry climate warming, $302 million/year results from lost agricultural production and $59 million/year is from urban water shortages. … Dry climate warming imposes an additional increase of $384 million/year in system operating costs. … With the climate warming, the costs of policies limiting interregional water transfers increases to $250 million/year." All together, these costs amount to $994 million per year, or less than 0.1% of California's $1.5 trillion/yr economy.

Columbia River & Pacific Northwest.

The Climate Impacts Group at University of Washington assessed the impacts of climate change on the Pacific Northwest and the state of Washington, averaging across 20 GCMs under both SRES B1 and A1B (Climate Impacts Group, 2009). Snowpack reductions were significant, with snow water equivalent falling by as much as 65%. Although annual runoff shows an increase of 6% there is a reduction of 43% in runoff during the summer irrigation season by the 2080s. Without adaptation water delivery shortages to agriculture in the Yakima River basin, for example, could be significant. Estimated deliveries fall by as much as 77% by the 2080s. In the 2020s, regional hydropower production increases by 0.5-4% in winter, decreases by 9-11% in summer, with annual reductions of 1-4%.Economic losses of between $23 million and $70 million are estimated, with significantly greater probabilities of annual net operating losses for junior water rights holders.

Rio Grande.

Hurd and Coonrod (2007) estimate economic impacts of climate change on water resources in the Upper Rio Grande (primarily New Mexico, El Paso, Tx, and the San Luis Valley of Southern Colorado). Under the relatively dry scenario (GFDL), runoff change was estimated to fall by 28% (using WATBAL) and annual direct economic damages in 2080 were estimated at $100 million using a hydro-economic model of the watershed. This loss is approximately 0.2% of the estimated GSP of $60 billion.

Colorado River.

Christensen and Lettenmaier (2007), did a similar research on the Colorado River hydrology with the average of 11 GCM ensembles and two SRES emission scenarios: A2 and B1 (reference). Annual runoff reduction was between 0.0 (2020 B1) and 11.0 (2080 A2) percent. Average annual delivery shortage was estimated to be between 0.22 BCM/Yr (115.8%) and 1.2 BCM/Yr (631.5). Energy Production is estimated to increase during 2020s by the maximum of 120.5 GWh/Yr (1.4%) and experience a reduction during the rest of the century which will result in a maximum of 1573.6 GWh/Yr (18.5%) of negative production during 2080s.

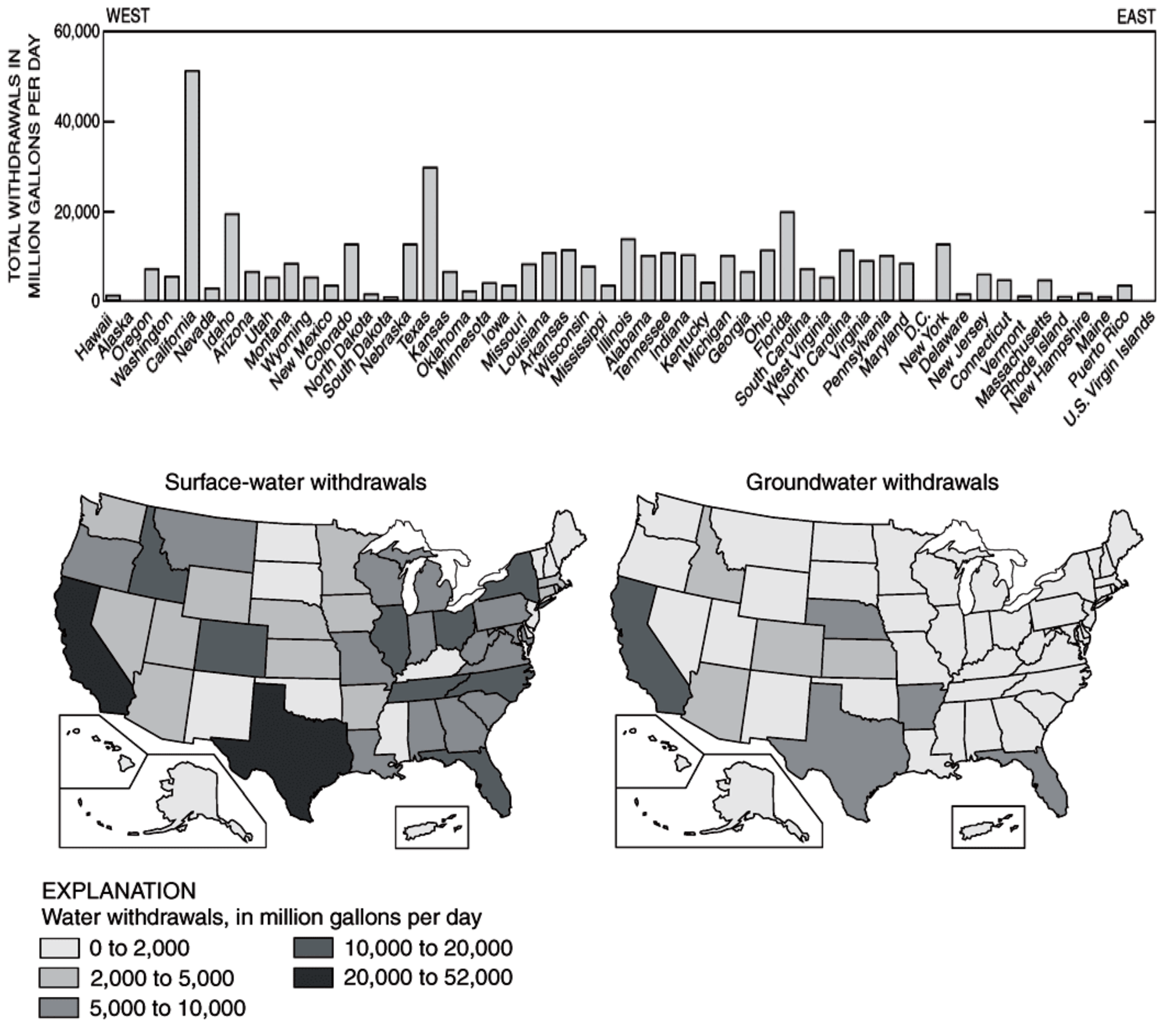
Hurd et al. (1999a), following the work of Booker and Young, modeled the hydro-economy of the Colorado River basin and the impacts of climate change using incremental climate change scenarios and the VIC hydrology model. From an annual baseline of $7.7 billion (1994$) they estimated economic losses for a 5 deg C rise with no change in precipitation of nearly $1.2 billion when runoff was estimated to fall by 35%. Under a 2.5 deg C rise and a 10% reduction in precipitation the losses approached nearly $1.4 billion (1994$).

Other Regions.

A few other regional studies of economic climate change impacts have been documented. Our survey is neither exhaustive nor comprehensive, though literature searches do not find many that are geographically broad. This does not indicate that there are not likely to be significant impacts in other regions. Exhibit 4 shows some of the other basins modeled by Hurd et al. (1999a) and the estimated changes in runoff and economic impact.

Exhibits

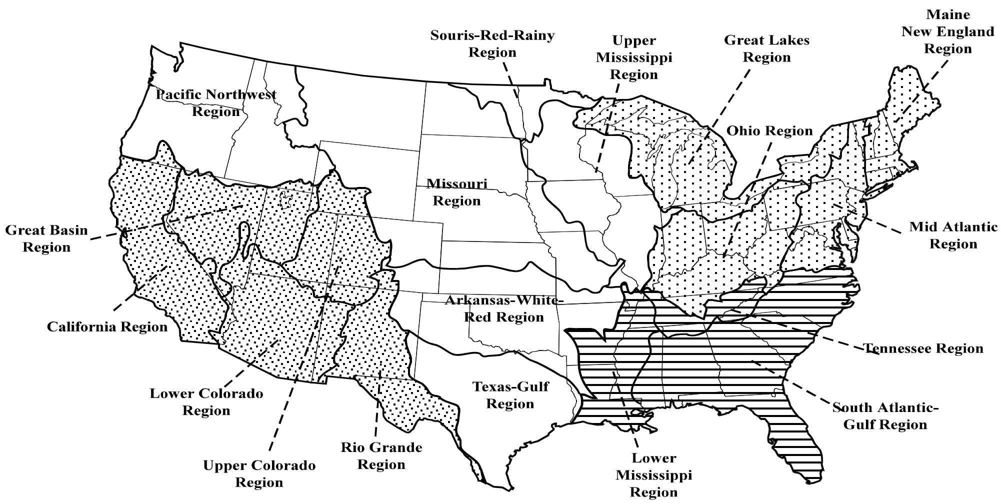
Exhibit 1. Estimated Use of Water in the United States in 2000 Including Surface Water and Groundwater Withdrawals source: USGS (2000)



Source: USGS (2000).

Exhibit 2. a. U.S. Water Resource Regions and the Regional Associations and b. Estimated National Level Impacts of Climate Change on Water Resources from Hurd et al. (1999a, 2004)

a.



b.

Estimated Total Economic Welfare Impacts on U.S. Water Resource Users (billions of 1994$)				
		Nonconsumptive Use		
Climate Scenario	Consumptive Use	Hydropower	Other Nonconsumptive Sectors*	Total
Baseline	88.5	14.7	28.7	132.00
+1.5°C +15%P	0.085	0.69	8.98	9.76
+2.5°C +7%P	-0.98	-2.75	-5.68	-9.41
+5.0°C	-4.29	-7.42	-31.4	-43.11
* Not including damages from thermal heat pollution.				

Exhibit 3. Excerpted from Backus et al. (2010), Cumulative GDP climate-change risk (40 years from 2010–2050) from reduced precipitation for the ensemble of A1B climate scenarios (in billions of dollars at a 0% discount rate).

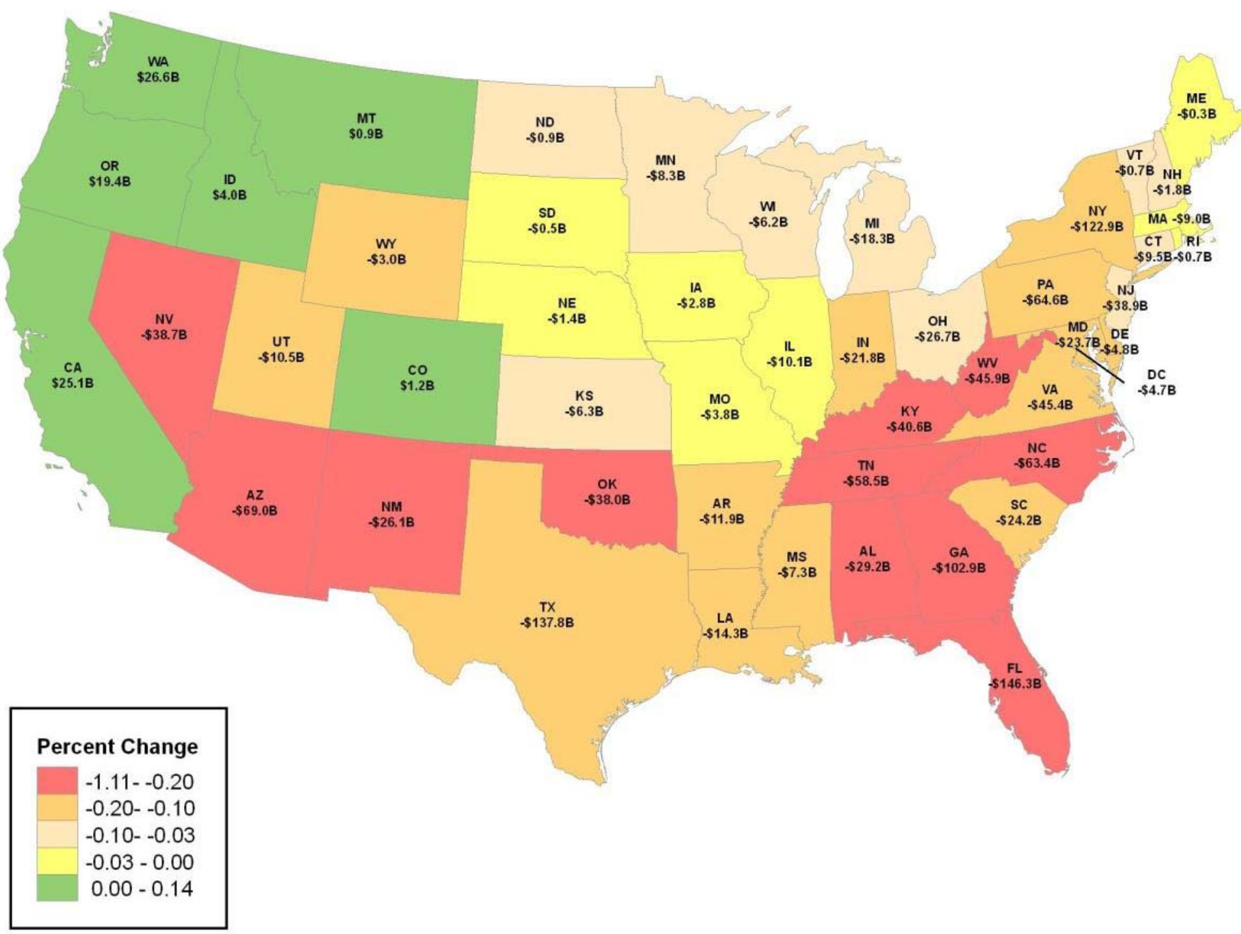


Exhibit 4. Estimated Regional Changes in Runoff and Economic Welfare under Selected Incremental Climate Changes

	Watershed			
	Colorado	Missouri	Appalachicola-Flint-Chattahoochie	Delaware
Baseline				
Runoff (kaf/yr)	17,058	56,651	24,363	13,660
Welfare (million 1994$)	$7,744	$10,804	$2,225	$6,565
Climate Change Scenario and Changes from Baseline				
+2.5 deg C, +7% P				
% Runoff chg (kaf/yr)	- 4.2%	- 9.1%	- 0.3%	- 4.1%
Welfare chg (M1994$)	- $102	- $519	- $15 (1)	- $22
+2.5 deg C, -10% P				
% Runoff chg (kaf/yr)	- 37.9%	- 42.5%	- 27.5%	- 33.2%
Welfare chg (M1994$)	- $1,372	- $2,041	- $12 (1)	- $187
+5 deg C, 0% P				
% Runoff chg (kaf/yr)	- 34.7%	- 42.4%	- 23.5%	- 33.9%
Welfare chg (M1994$)	- $1,193	- $2,239	- $31 (1)	- $207

(1) The estimated changes in welfare for the AFC basin show a mixture of effects including changes in flooding and water quality which confound simple comparison across scenarios. For example, a possible consequence of warmer and drier mean climate might be an expected reduction in average annual flood damages as represented in the above results. However, this analysis does not take into account possible changes in climate variability i.e., greater frequency and intensity of extreme events.

Source: Adapted from: **Hurd, B. H., J. M. Callaway, J. B. Smith, and P. Kirshen**. 1999a. "Economic Effects of Climate Change on U.S. Water Resources." In *The Impact of Climate Change on the United States Economy*. ed. Robert Mendelsohn and James NeumannCambride, UK: Cambridge University Press, 133-177.

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Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis

Sponsored by EPA United States Environmental Protection Agency; U.S. Department of Energy

January 27-28, 2011 Capital Hilton, Washington, DC

Research on Climate Change Impacts and Associated Economic Damages:

Estimates of the Economic Impact of Changes in Climate and Water Availability

Brian H. Hurd

Assoc. Prof of Agricultural Economics & Agricultural Business
New Mexico State University

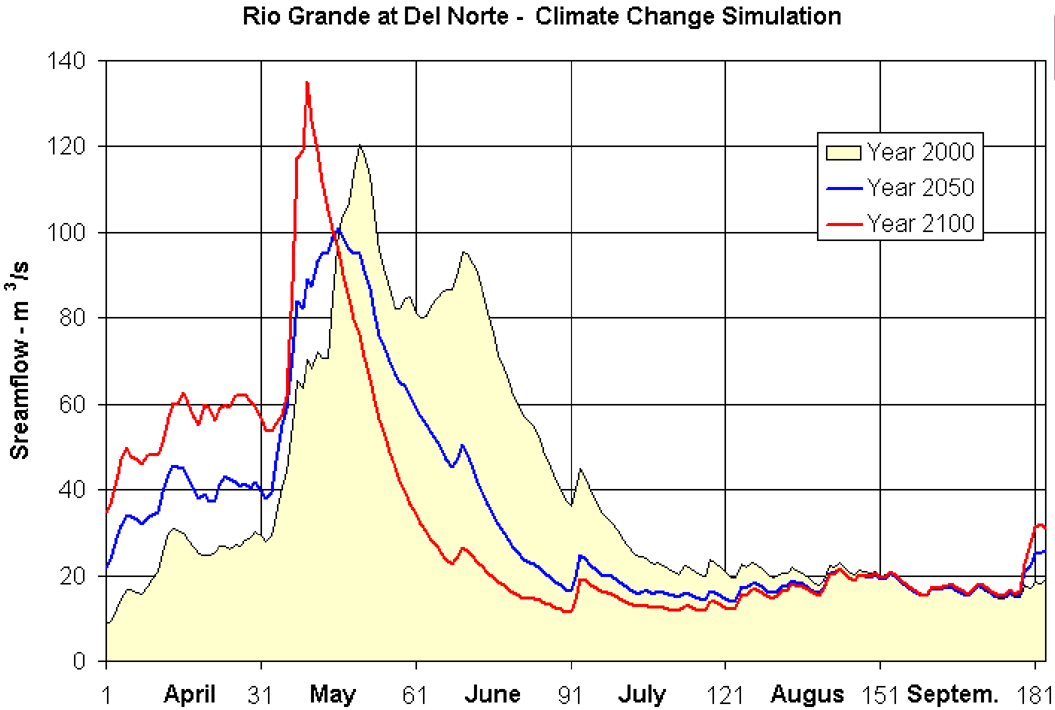
Overview

- Concepts and Complexities
- National Estimates
- Regional Estimates
- Issues, Gaps, and Next Steps

Water, Climate & Communities Form Complex Systems

- Estimating water resource impacts is tough
  - Lots of variability: spatial, temporal, uses, infrastructure, vulnerability
- What to measure?
  - Economic damages/benefits?
  - Changes in jobs, income & production?
- How to measure?
  - Statistical models?
  - Simulation models?
  - Optimization models?
- Adaptation & behavior

Climate and Rivers



Model assumptions

temperature ↑ 4°C

Precipitation ↑ 10%

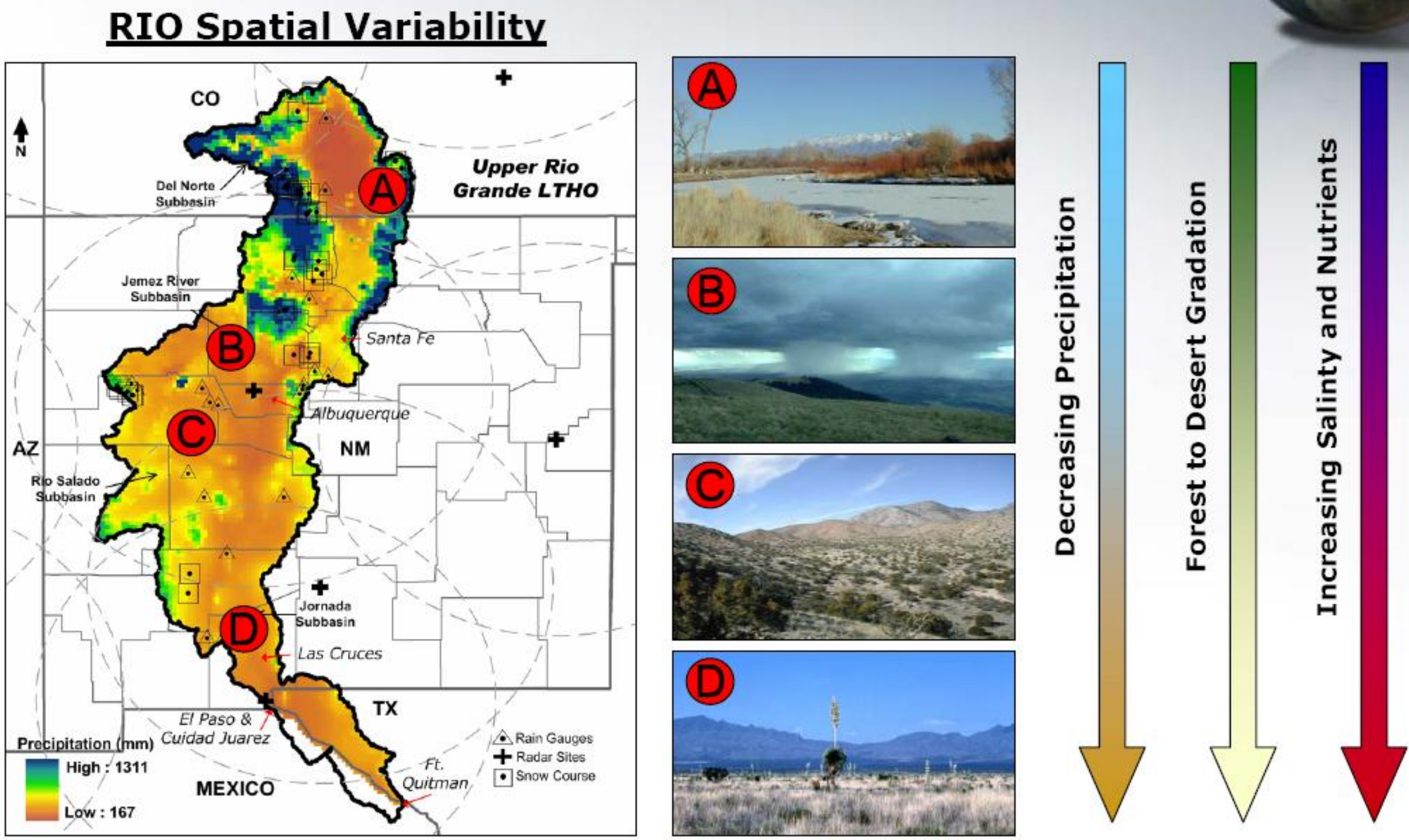
source: Al Rango (usda/ars)
using Snow melt Runoff Model (SRM)

What does it mean for?

- Water storage and distribution systems?
- Urban and rural water users?
- Water quality?
- Hydropower?
- Recreational and cultural functions?
- Riparian ecosystems and migratory patterns?

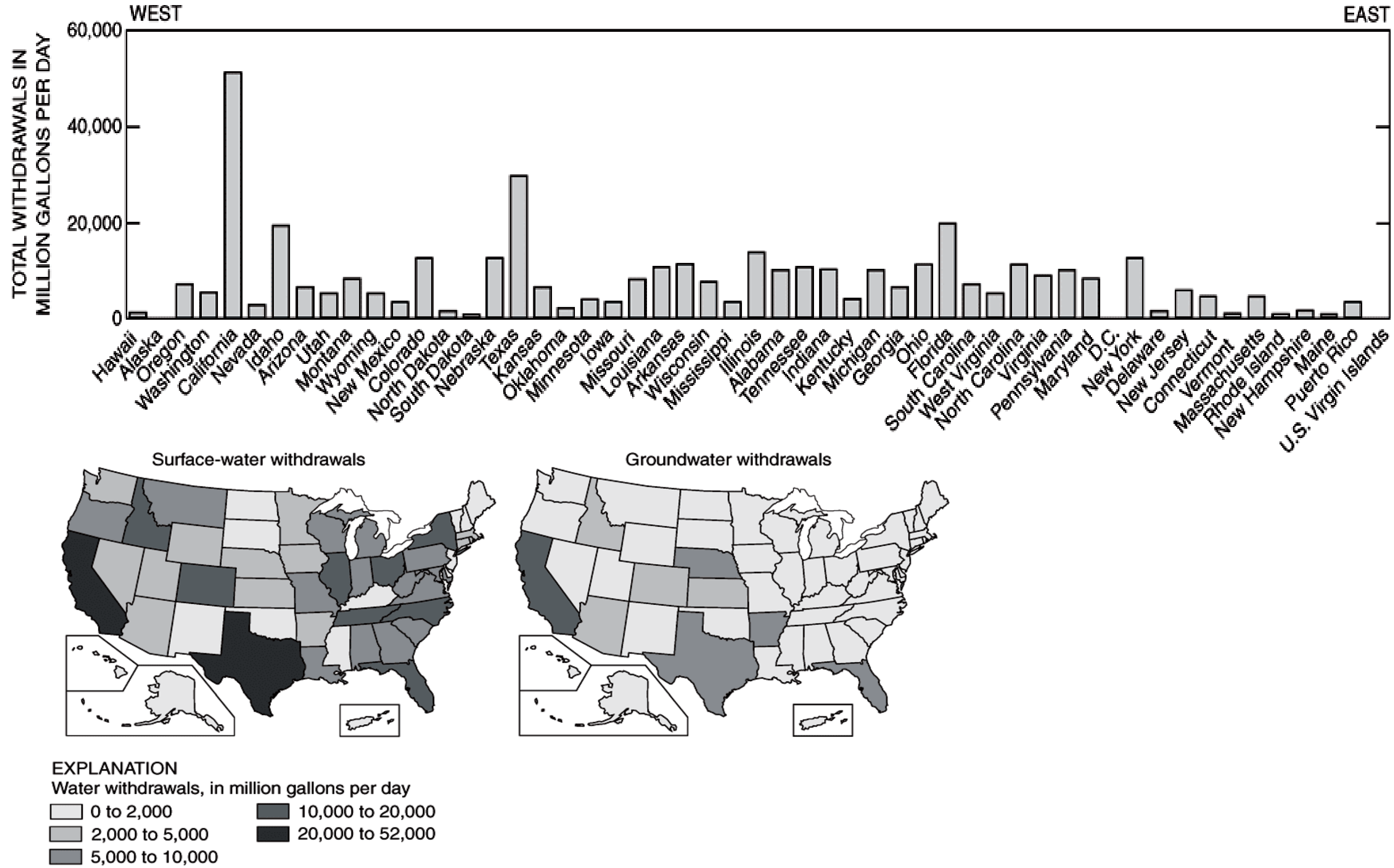
Spatial Heterogeneity: Climate, Vegetation, Environment

Upper Rio Grande



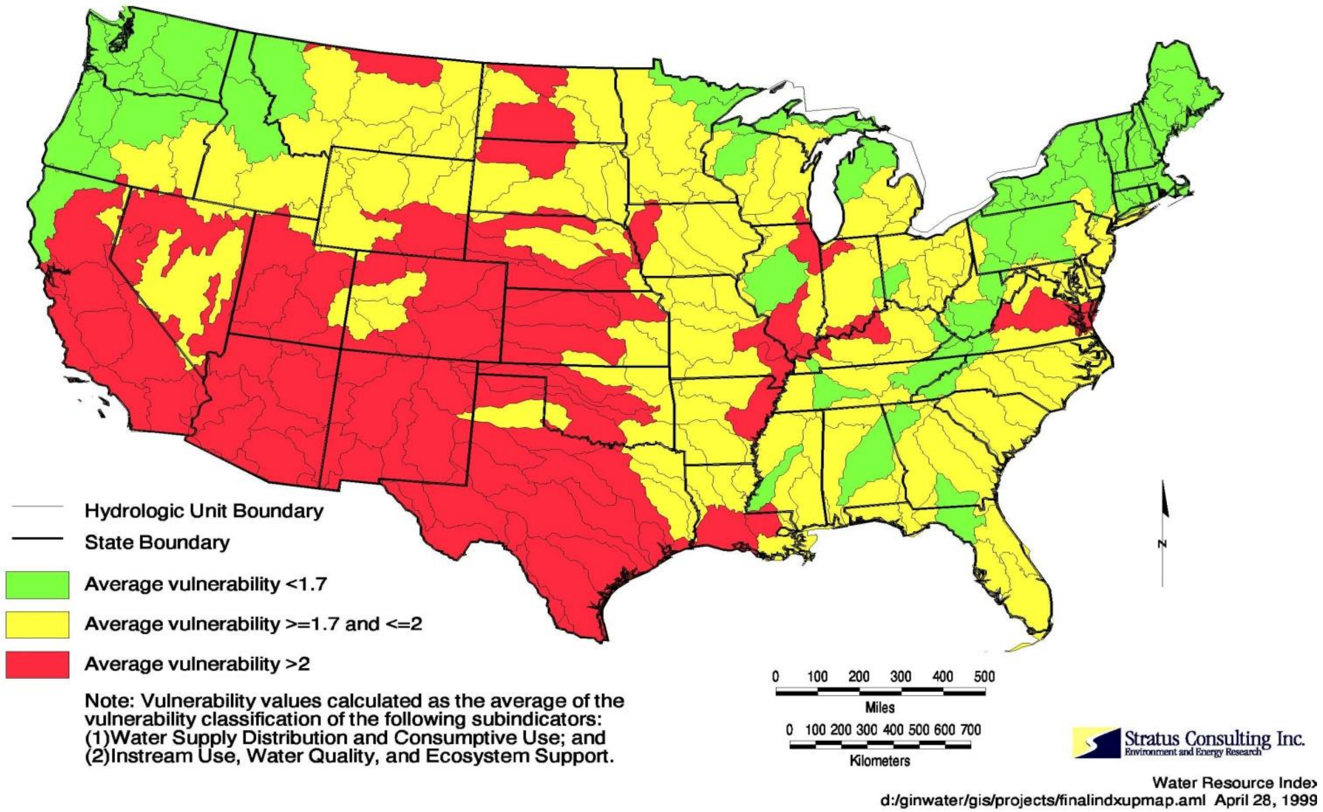
Source: Enrigue Vivoni, AZ State Univ.

Water Use Patterns



Source: USGS (2000).

Relative Regional Vulnerability of Water Resources



Overall Index

Source: Hurd, B.H., N. Leary, R. Jones, and J.B. Smith. 1999. "Relative Regional Vulnerability of Water Resources to Climate Change." *Journal of the American Water Resources Association*, December, 35(6): 1399-1410.

National Estimates: Summary

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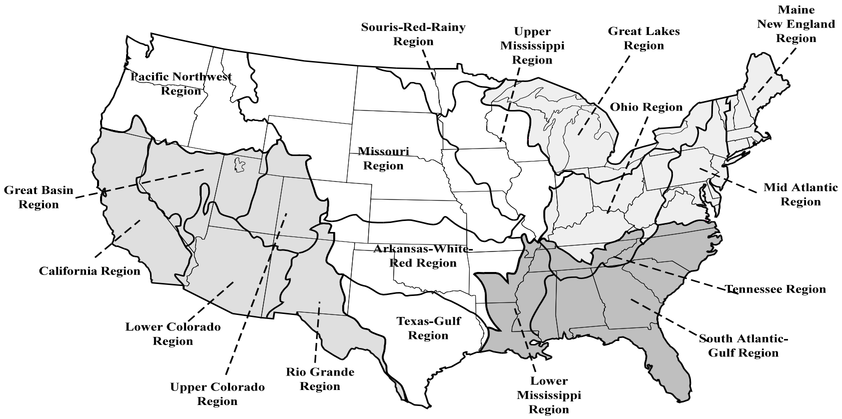
Backus et al. (SANDIA, 2010)	$ 60 billion (~ 0.4% of 2009 US-GDP $14.1 trillion)

National Estimates: Aggregating Benefits and Costs
Hydro-economic Model Approach



Estimated Total Economic Welfare Impacts on U.S. Water Resource Users (billions of 1994$)

Climate Scenario	Consumptive Use	Nonconsumptive Use: Hydropower	Nonconsumptive Use: Other Nonconsumptive Sectors*	Total
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+1.5°C +15%P	0.085	0.69	8.98	9.76
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* Not including damages from thermal heat pollution.

Source: Hurd, B. H., J. M. Callaway, J. B. Smith, and P. Kirshen. 1999.
"Economic Effects of Climate Change on U.S. Water Resources."
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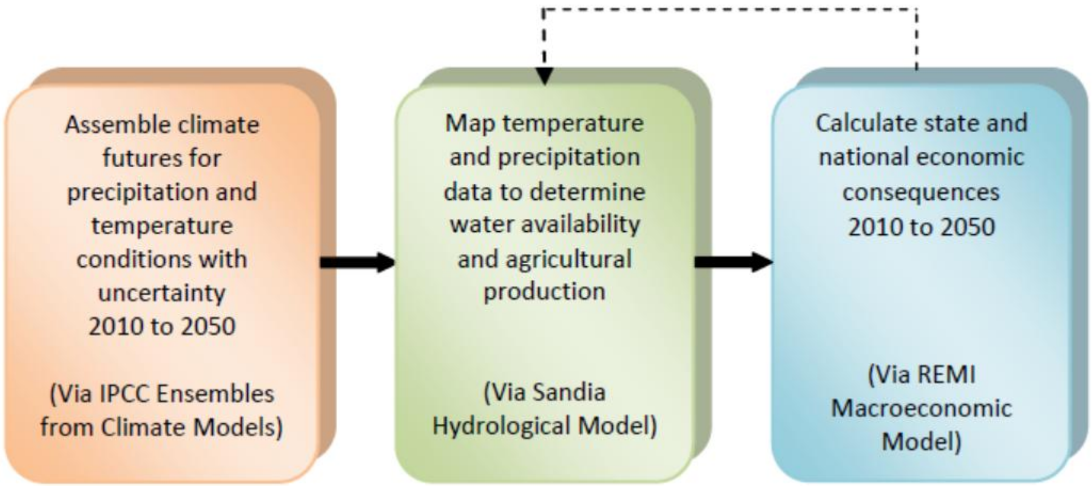
Cambride, UK: Cambridge University Press, 133-177. .

National Estimates: Jobs, Income & GDP Approach



Sandia National Laboratory (Backus et al., 2010) estimates there is a 50-50 chance that cumulative direct and indirect macro-economic losses in GDP through 2050 will exceed nearly $ 1.1 trillion (2008$), not including flood risks. That is approximately 0.2% of the cumulative GDP projected between 2010 and 2050.

On an annual basis: a 50-50 chance of non-discounted losses of $60 billion (2008$) by 2050.

Source: Backus, G. et al. ***Assessing the Near-Term Risk of Climate Uncertainty: Interdependencies Among the U.S. States***. SAND2010-2052, 1-259. 2010. Albuquerque, New Mexico, Sandia National Laboratories.

Regional Estimates: Hydro-economic Model Approach

Estimated Regional Changes in Runoff and Economic Welfare under Selected Incremental Climate Changes

	Watershed			
	Colorado	Missouri	Appalachicola-Flint-Chattahoochie	Delaware
Baseline				
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Welfare (million 1994$)	$7,744	$10,804	$2,225	$6,565
Climate Change Scenario and Changes from Baseline				
+2.5 deg C, +7% P				
% Runoff chg (kaf/yr)	- 4.2%	- 9.1%	- 0.3%	- 4.1%
Welfare chg (M1994$)	- $102	- $519	- $15 (1)	- $22
+2.5 deg C, -10% P				
% Runoff chg (kaf/yr)	- 37.9%	- 42.5%	- 27.5%	- 33.2%
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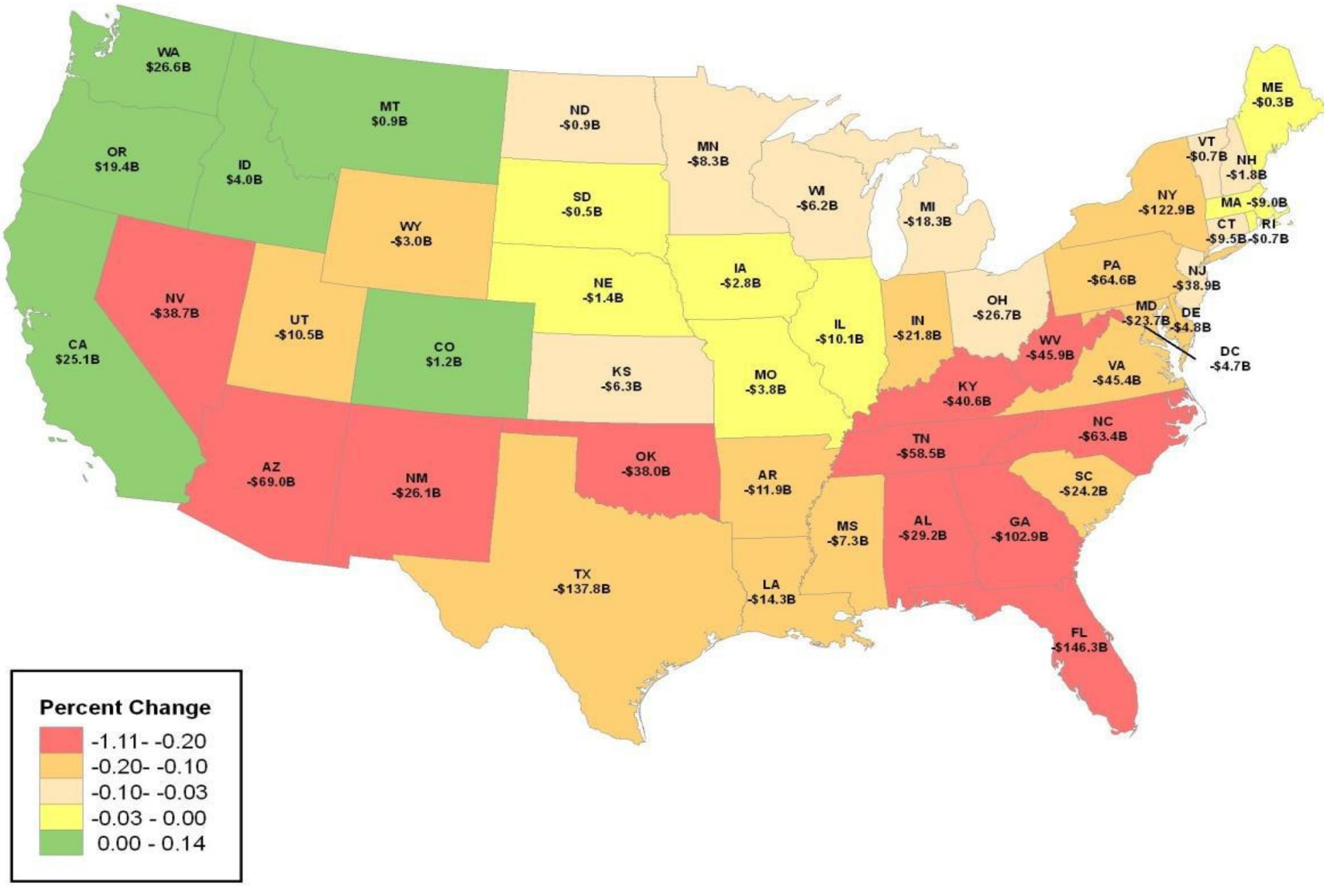
Welfare chg (M1994$)	- $1,193	- $2,239	- $31 (1)	- $207

Source: Hurd, B. H., J. M. Callaway, J. B. Smith, and P. Kirshen. 1999.

Other Regional Estimates

Region	Study	Economic Impacts
California	Medellin et al. (2006)	$302 M/yr agricultural scarcity cost, $59 M/yr urban scarcity cost, $384 M/yr operating cost, $250 M/yr the costs of policies limiting interregional water transfers, which is $994 M/yr totally (less than 0.1% California's economy)
Pacific Northwest	Climate Impacts Group (2009)	Economic losses of between $23 million and $70 million are estimated, with significantly greater probabilities of annual net operating losses for junior water rights holders.
Rio Grande	Hurd and Coonrod (2007)	direct economic damages in 2080 were estimated to be $100 million/year
Colorado River	Christensen and Lettenmaier(2007)	Energy Production is estimated to increase during 2020s by the maximum of 120.5 GWh/Yr (1.4%) and experience a reduction during the rest of the century which will result in a maximum of 1573.6 GWh/Yr (18.5%) of negative production during 2080s.

State-Level Estimates: SANDIA/REMI Approach



Source: Backus, G. et al. ***Assessing the Near-Term Risk of Climate Uncertainty: Interdependencies Among the U.S. States***. SAND2010-2052, 1-259. 2010. Albuquerque, New Mexico, Sandia National Laboratories.

Issues, Gaps, and Next Steps

- Understanding changes in extreme events
  - Severe, sustained drought risk
  - Flood risk changes are not well understood and are often locally sensitive
- Water rights, federal & state regulation, and administration constraints confound assessment of impacts and adaptation
- Projecting market prices and trade flows of agricultural and other water-intensive products is difficult
- Groundwater. Measuring, monitoring, modeling.
- Water security and food security are conflated and stir deep emotions
- Water quality and environmental quality hard to assess and measure economic outcomes
- Coupling of hydro-economic and dynamic system simulation approaches could bridge some gaps

More information can be found at:
http://agecon.nmsu.edu/bhurd

Biophysical Climate Change Effects on Agro-ecosystems

U.S. EPA/DOE Workshop

Research on Climate Change Impacts and Associated Economic Damages

January 27-28, 2011

Cynthia Rosenzweig

NASA/Goddard Institute for Space Studies

Outline

- **Estimates of current and likely impact of climate change on biophysical response of agricultural crops**
- **Data and models used to make projections**
- **Modulation of biophysical impacts via adaptation**
- **Gaps and uncertainties**

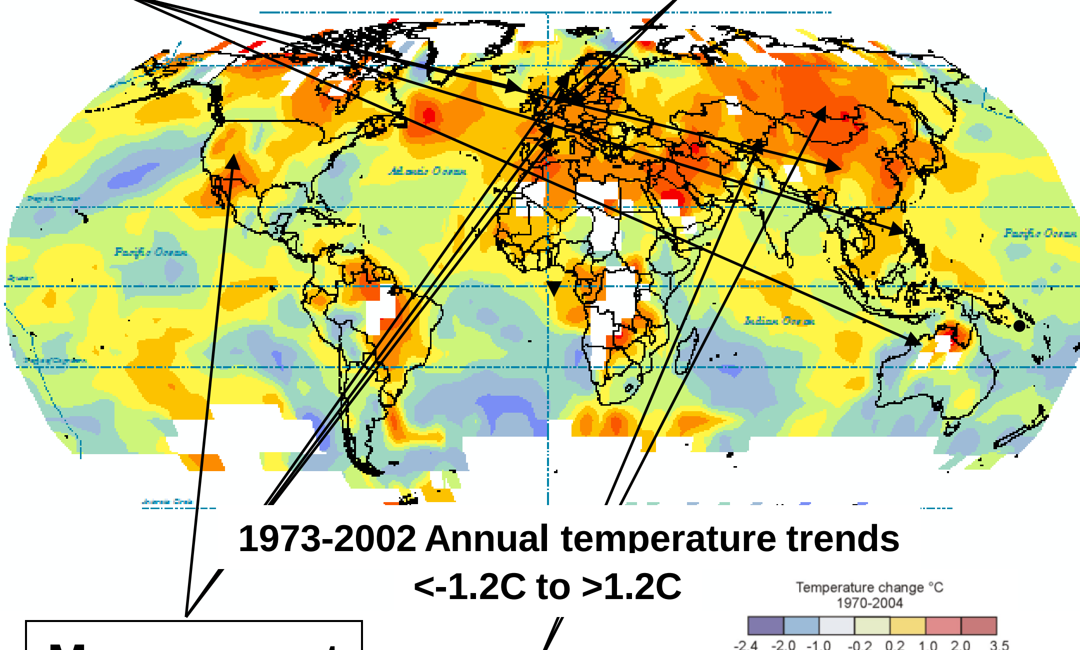
Current and Future Impacts

- Estimates of the current and likely future impact of climate change on biophysical response of agricultural crops.
  - What crops, (livestock), soil, and pests will be most affected?
  - Describe the best central estimates, the wider range of possible outcomes, and the relative likelihood of those outcomes.

Observed Impacts on Agriculture

Yields

Phenology



1973-2002 Annual temperature trends
<-1.2C to >1.2C

Management practices, forest fires, earlier pests and diseases

Livestock

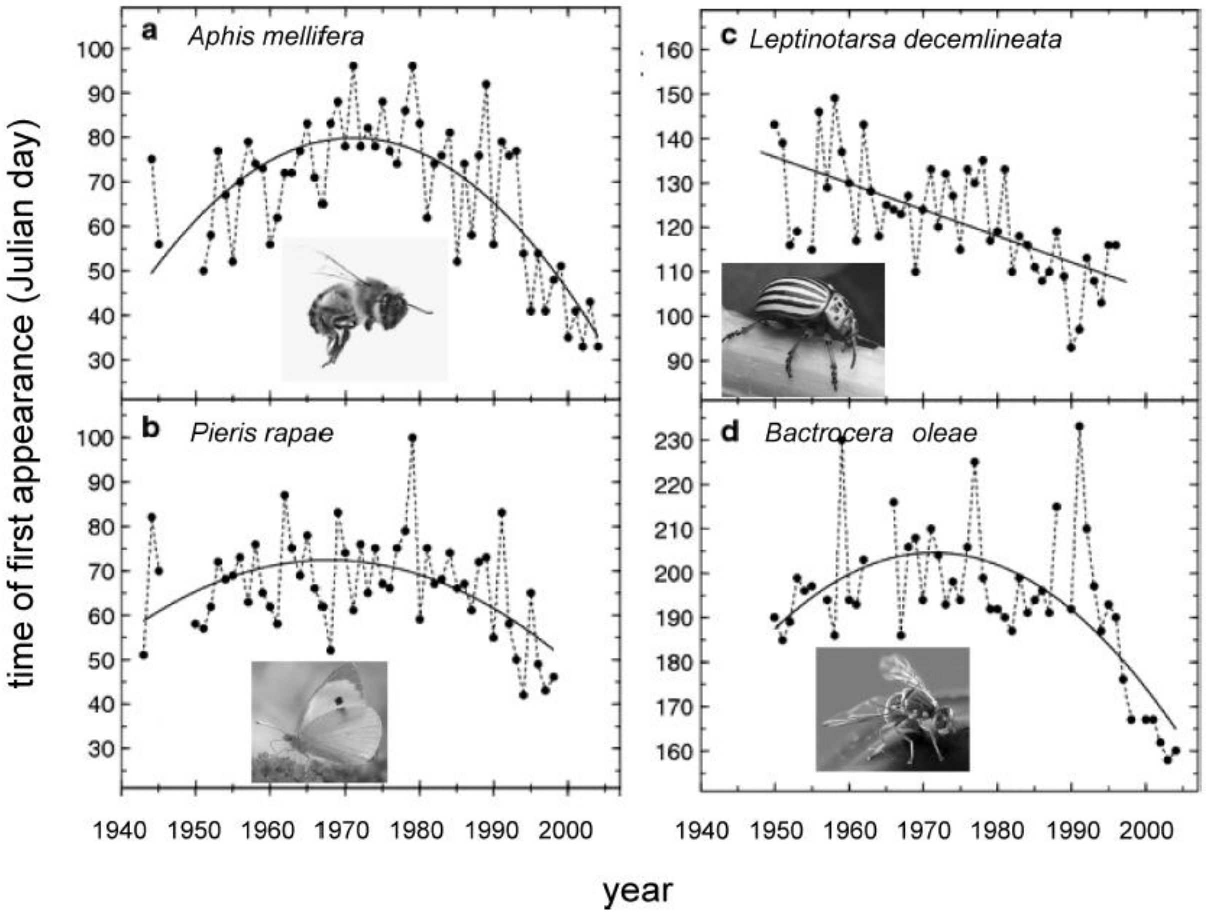
Over the last 50 years:

- *Very likely*
  - less frequent cold days, cold nights, and frosts
  - more frequent hot days and hot nights
- *Likely*
  - more frequent heat waves
  - more frequent heavy precipitation events
  - increased incidence of extreme high sea level
  - increased drought in some regions

High temperature effect on rice yield; Earlier planting of spring crops; Increased forest fires, pests in N America and Mediterranean; Decline in livestock productivity

IPCC WGII AR4

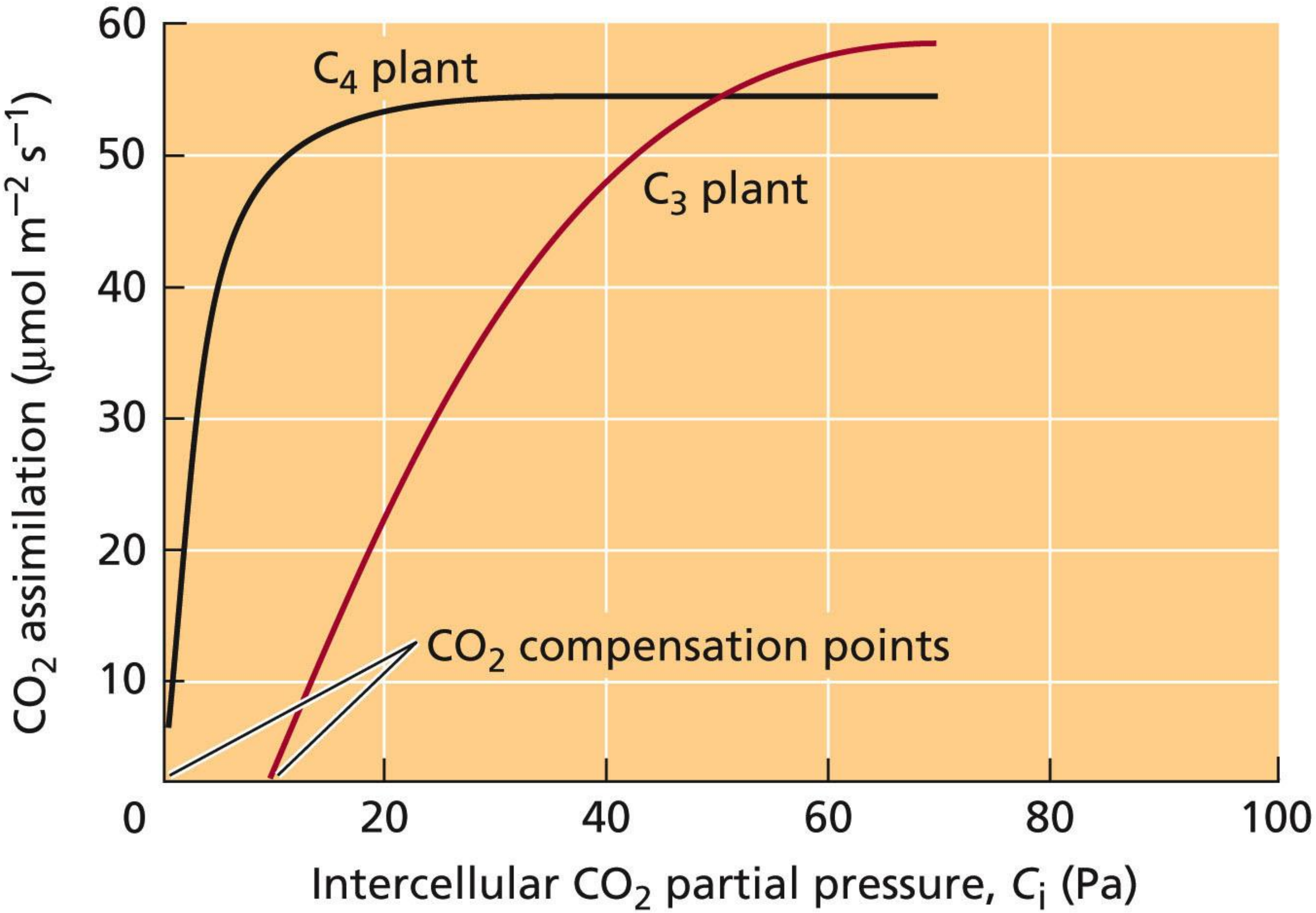
Earlier Emergence of Insects



In a six-decade long study at a biological research station in Spain, increasing earlier time of first appearance for the honey bee, cabbage white butterfly, potato beetle and olive fly were found.

Gordon and Sanz, 2005; Gutierrez et al., 2010

Photosynthesis Response to CO_2



PLANT PHYSIOLOGY, Fourth Edition, Figure 9.22

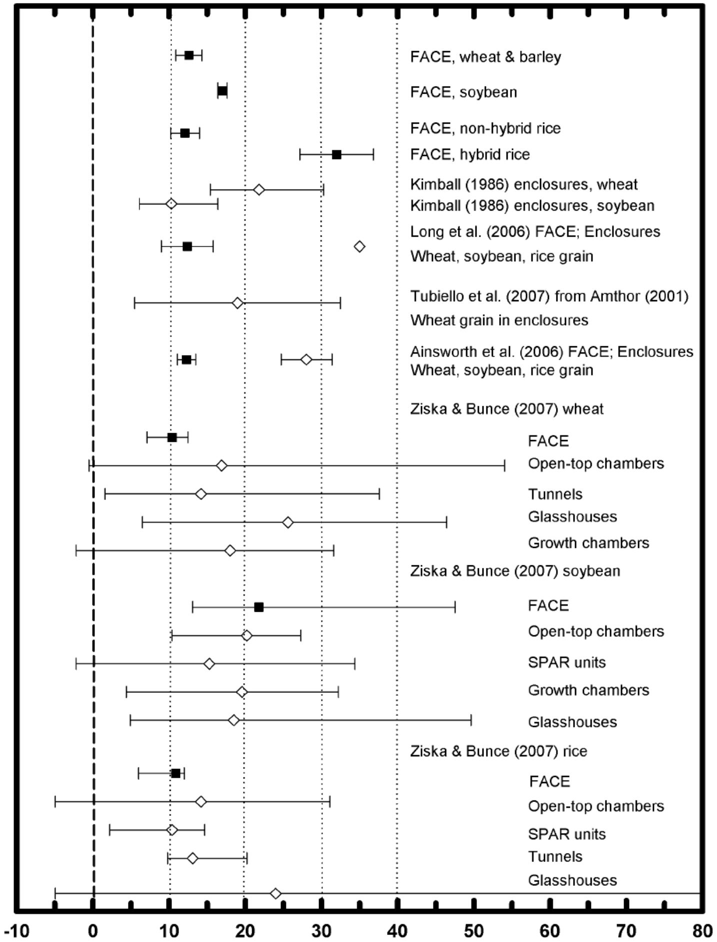
C_3 Plants

- Wheat
- Rice
- Soybean
- Barley

C_4 Plants

- Corn
- Sorghum
- Sugarcane

CO_2 Yield Responses



Relative C3 crop yield changes due to elevated CO_2 (%)

- Biomass and yield with +200ppm were increased by FACE in C3 species, but not in C4 except under water stressed conditions. Average C3 yield increase is ~16% in FACE.
- Low soil N often reduces these gains.
- It appears unlikely that there is a significant difference in the response of C3 grain crops to elevated CO_2 between FACE and enclosure experiments when the whole population of enclosure experiments is included and their variability is accounted for.
- Important for simulation.

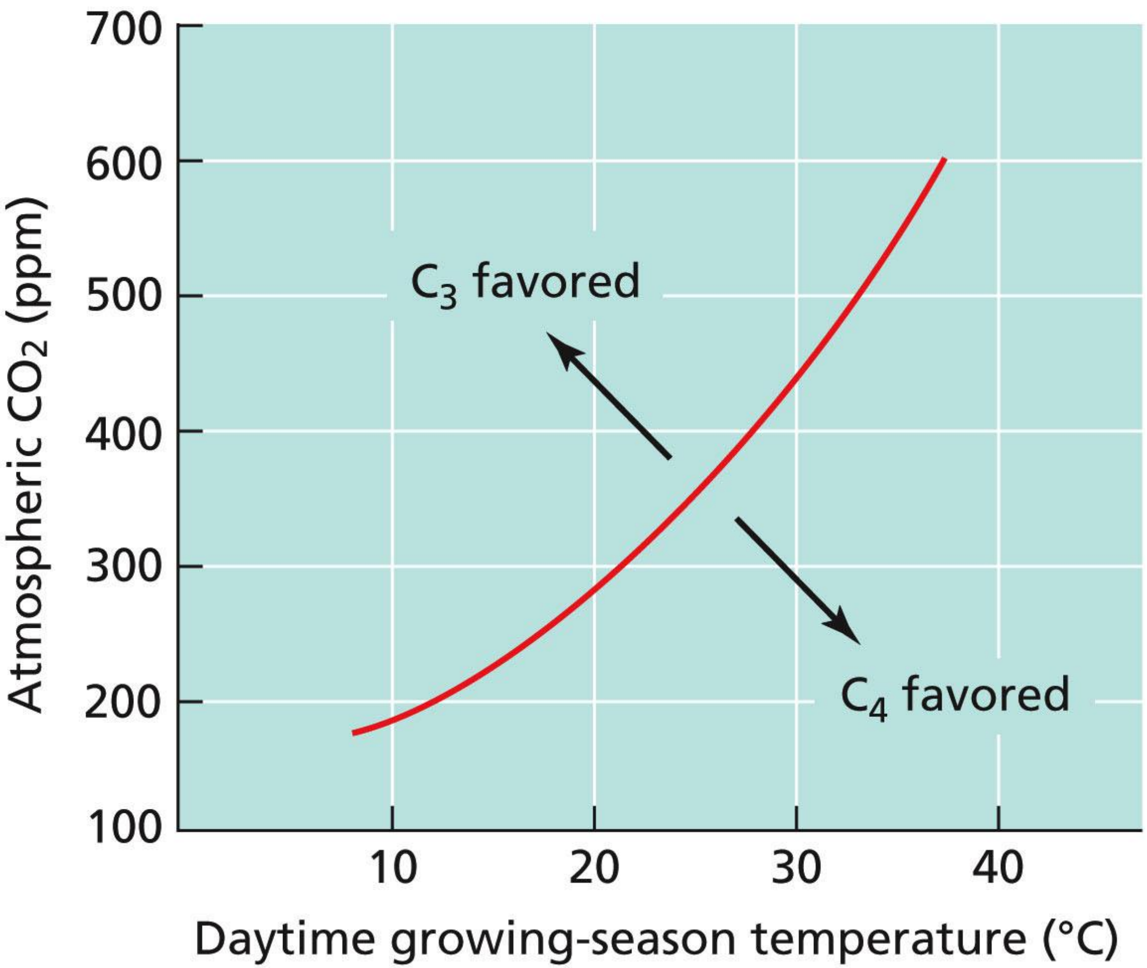
Kimball 2010

Elevated CO_2 can also favor weeds

Crop	Weed	Increasing $[CO_2]$ favors	Environment	Reference
A. C_4 Crops/C_4 Weeds				
Sorghum	*Amaranthus retroflexus*	Weed	Field	Ziska (2003)
B. C_4Crops/C_3 Weeds				
Sorghum	*Xanthium strumarium*	Weed	Glasshouse	Ziska (2001)
Sorghum	*Albutilon theophrasti*	Weed	Field	Ziska (2003)
C. C_3Crops/C_3 Weeds				
Soybean	*Chenopodium album*	Weed	Field	Ziska (2000)
Lucerne	*Taraxacum officinale*	Weed	Field	Bunce (1995)
Pasture	*Taraxacum and Plantago*	Weed	Field	Potvin and Vasseur (1997)
Pasture	*Plantago lanceolate*	Weed	Chamber	Newton *et al.* (1996)
D. C_3 Crops/C_4 Weeds				
Fescue	*Sorghum halapense*	Crop	Glasshouse	Carter and Peterson (1983)
Soybean	*Sorghum halapense*	Crop	Chamber	Patterson *et al.* (1984)
Rice	*Echinochloa glabrescens*	Crop	Glasshouse	Alberto *et al.* (1996)
Soybean	*A. retroflexus*	Crop	Field	Ziska (2000)

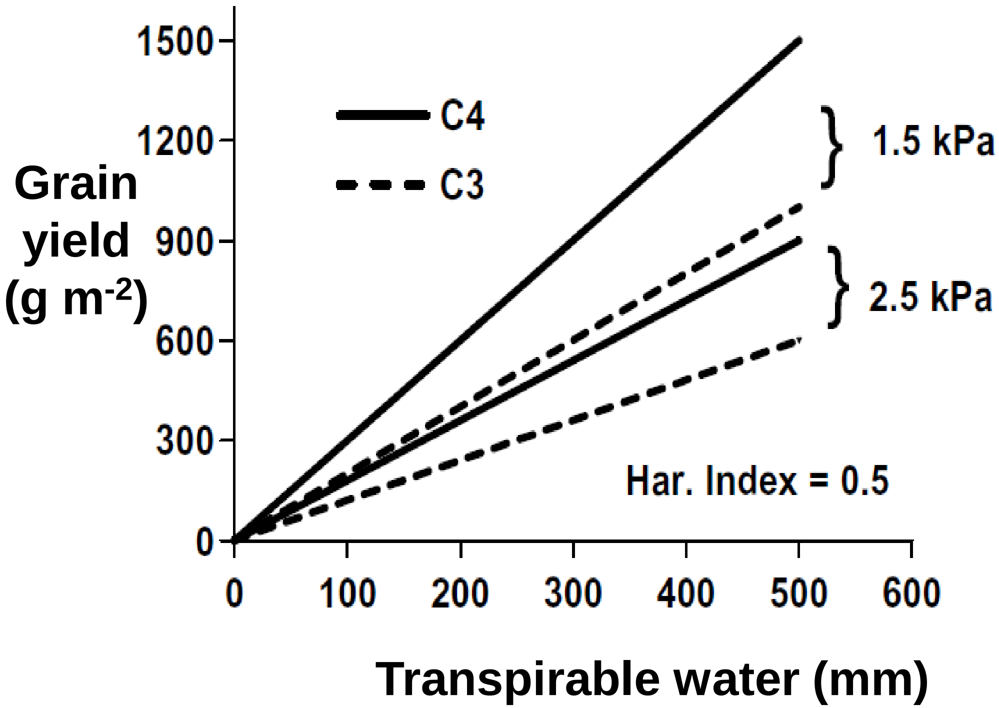
Ziska 2010

Crop Response to Temperature



- Can shift photosynthesis curve positively
- Speed-up of phenology is a negative pressure on yield
- High-temperature stress during critical growth periods
- T-FACE experiments now underway.

Yield Response to Water
Extreme events – Drought

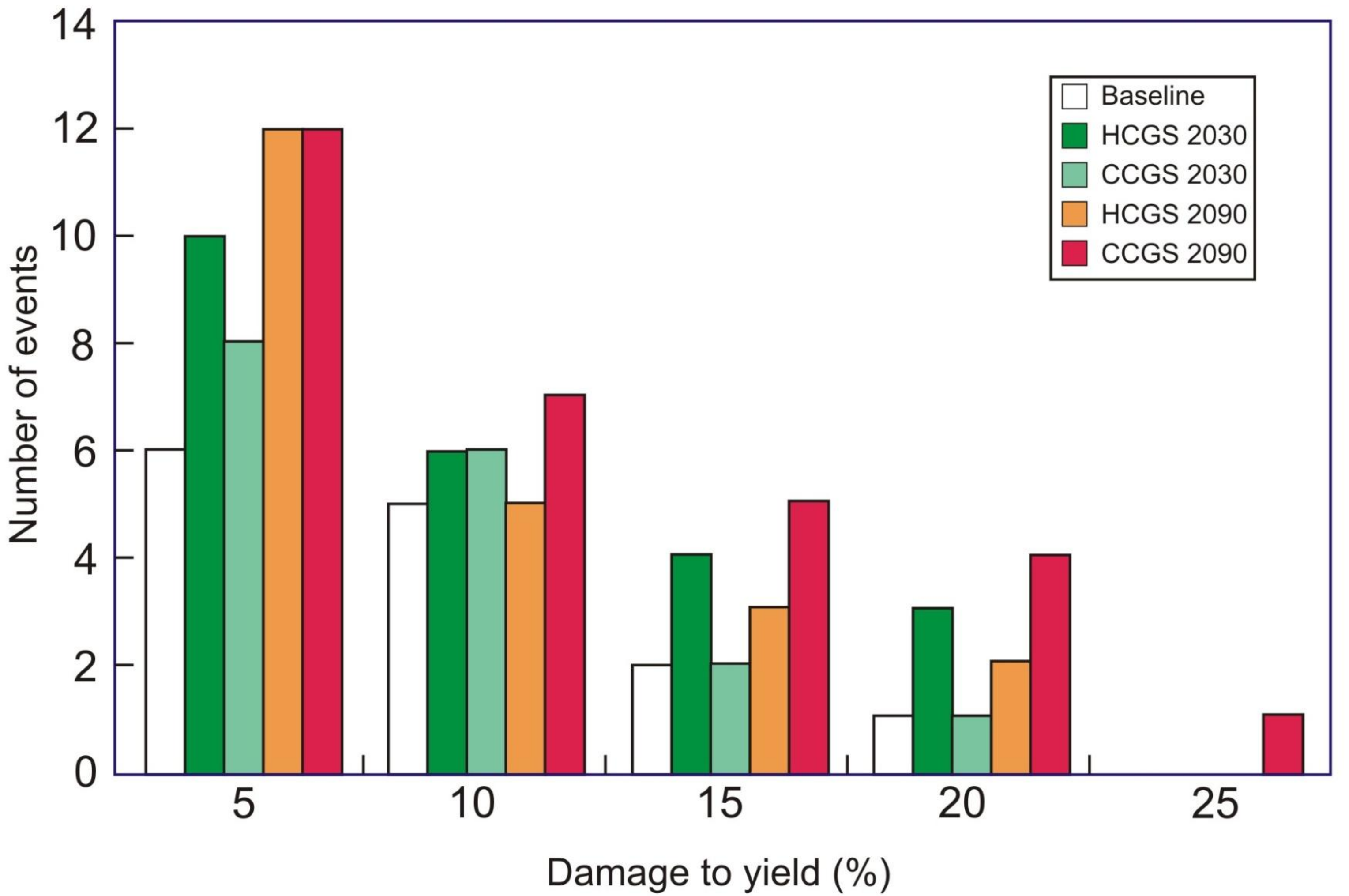


Maximum grain yield plotted as a function of the amount of transpirable soil water available through the growing season. Two vapor pressure deficit environments are presented. C4 crops favored at both higher and lower water stress.

- Crops need water – through precipitation or irrigation
- Drought stress affects yield during critical growth periods
- Excess water can be damaging as well

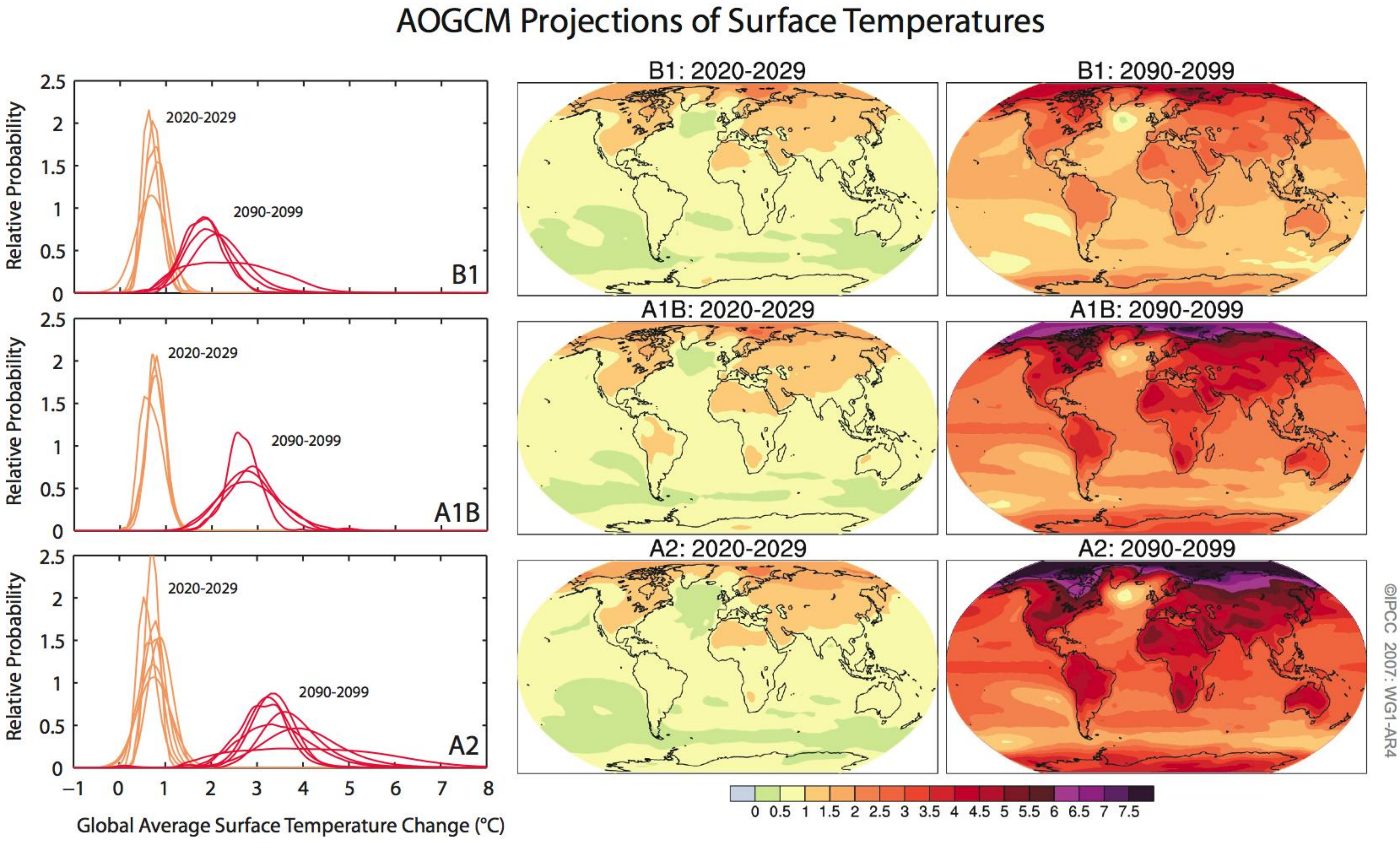
Sinclair 2010

Extreme Events – Floods



Number of events causing damage to maize yields due to excess soil moisture conditions, averaged over all study sites, under current baseline (1951–1998) and climate change conditions. Events causing a 20% simulated yield damage are comparable to the 1993 US Midwest floods.

Rosenzweig et al. 2001

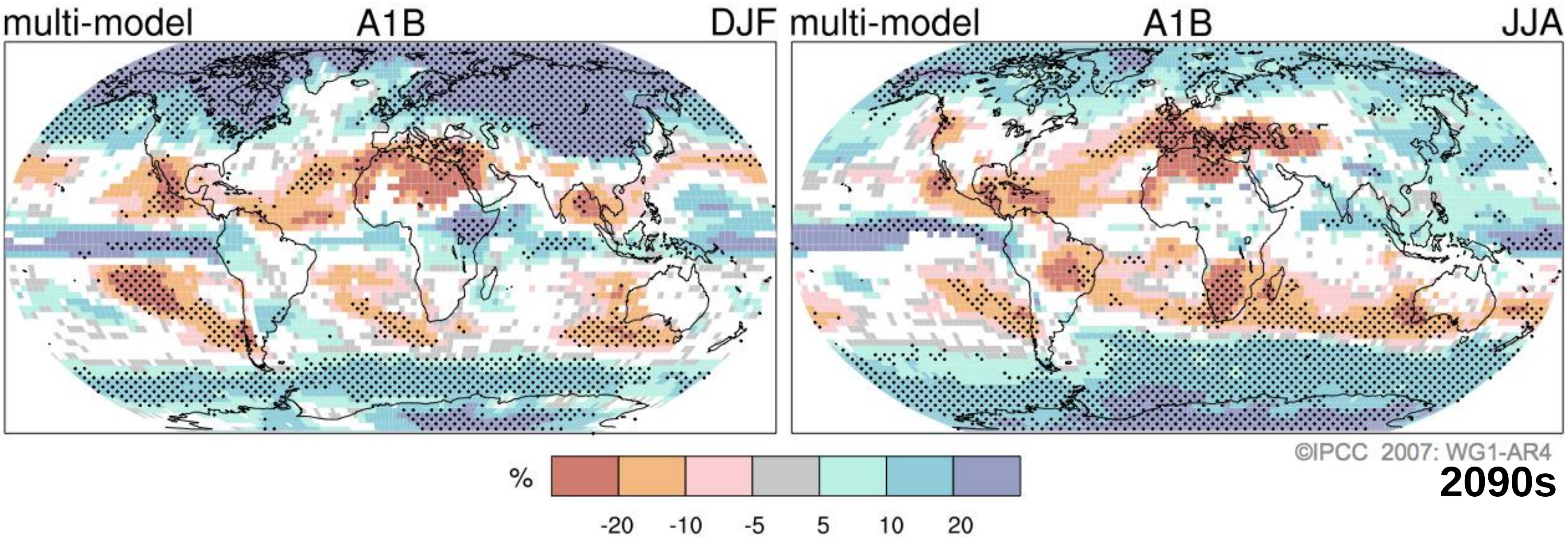


Warming is Expected to be Greatest over Land and at Most High Northern Latitudes.

Hot Extremes and Heat Waves will Continue to Become More Frequent

IPCC WGII AR4 Fig SPM-6

Projected Patterns of Precipitation Changes



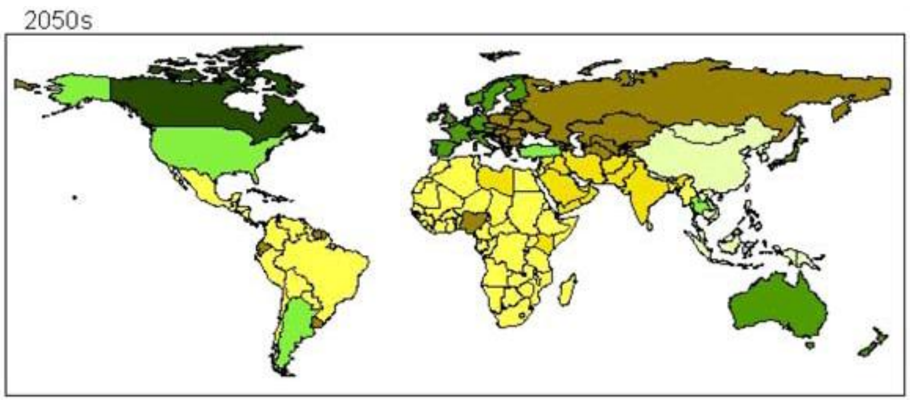
Increases in Precipitation are Very Likely in the High-Latitudes, while Decreases are Likely in Most Subtropical Land Regions

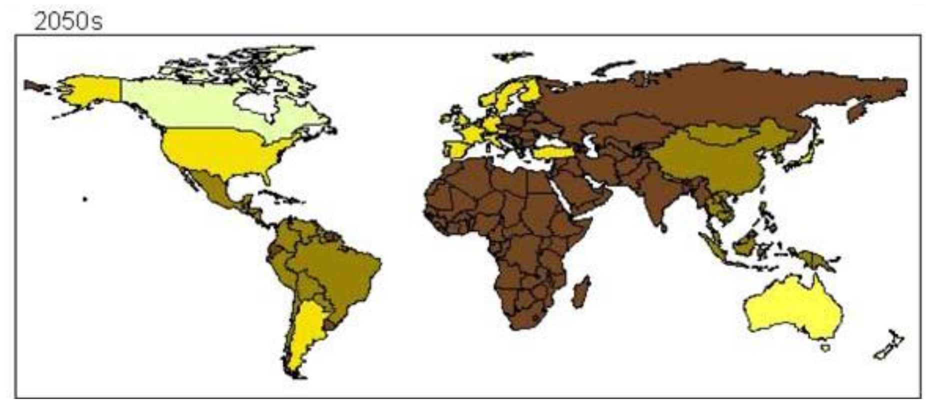
Heavy Precipitation Events will Continue to Become More Frequent

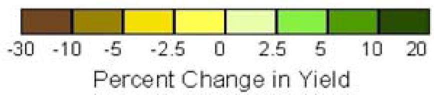
Droughts more frequent in some regions

IPCC WGI AR4 Figure SPM-7

Projected Yield Changes 2050s

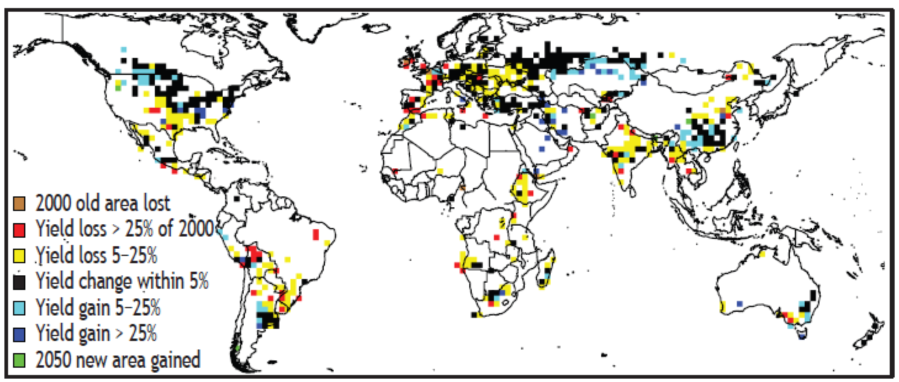






Parry et al., 2004

Potential changes (%) in national cereal yields for the 2050s (compared with 1990) under the HadCM3 SRES A2a scenario with and without CO_2 effects (DSSAT)



IFPRI 2011

Yield Effects with CO_2, rainfed wheat
CSIRO A1B (DSSAT)

Parry et al.	-30% to +20%
IFPRI	-25% to +25%
GAEZ	-32% to +19%

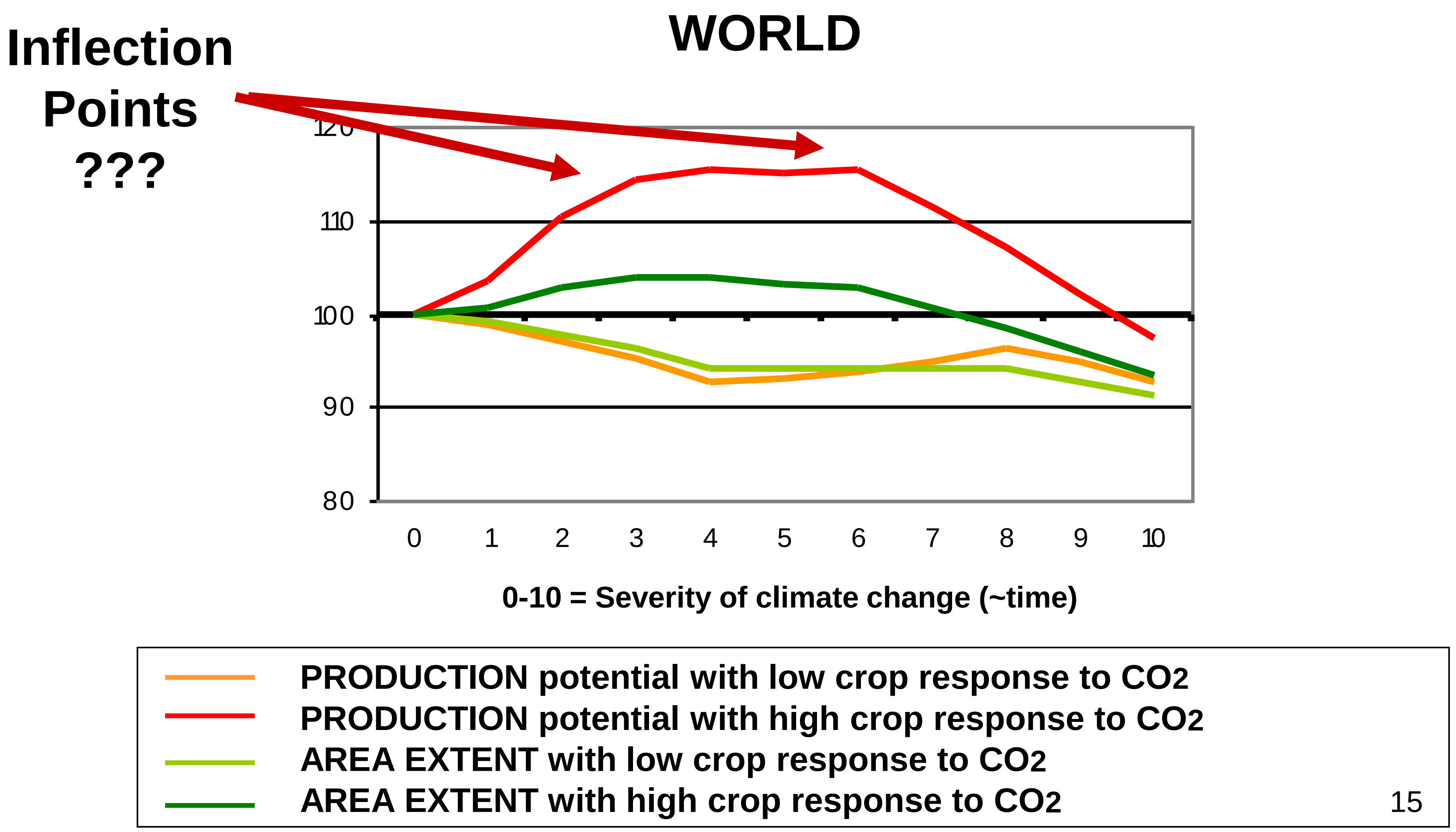
GAEZ IIASA 2009 rain-fed cereals Hadley A2
North America -7 to -1%; Europe -4 to 3;
Central Asia 14-19%; Southern Africa -32 to -29

Schlenker & Lobel Africa multi GCMs
-22 to -2% statistical approach

w/o adaptation

Global Effects of Climate Change are Positive in Short Term and Negative in Long Term

Percent Change in Food Production Potential



IIASA

Discuss the data and models used to make these projections.

Are some modeling methods superior to others?

What are the main data requirements, spatial resolution, and level of uncertainty in the outputs?

How are impacts expected to differ across temperate and tropical regions?

Statistical Approach

• Uses historical data to estimate statistical relationships between observed crop yields as a function of observed climate variables.

• Uses these relationships to project the yield impact of changes in climate.

Advantages

Relationships should integrate biophysical responses to climate variables; based on observations; data availability is improving.

Disadvantages

The approach does not explain process-based changes; does not represent out-of-sample conditions; does not incorporate the effects of CO_2.

Data: yearly yield/aggregated 1^o 4-hourly reanalysis, monthly, growing season, degree days climate; Spatial resolution: crop reporting districts; country level

Expert System Approach

• Uses soil capability, climate, crop calendar, and simple productivity relationships to estimate production potential of agricultural systems.

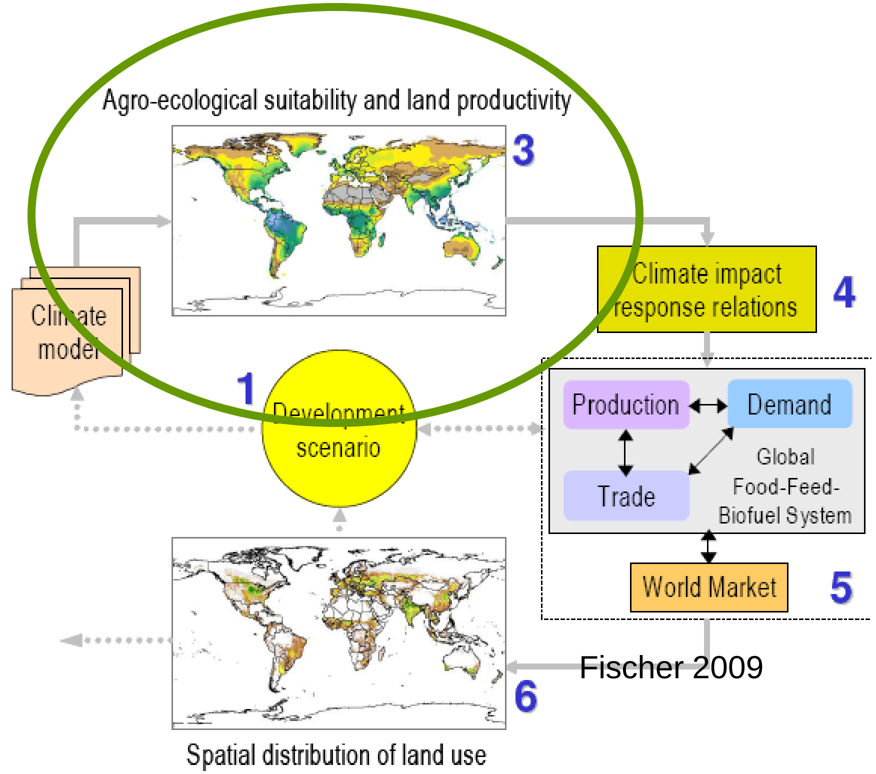
• Use calculator to project effect of changes in climate on production potential.

Advantages

Projects changes in both production potential and spatial extent of cropping systems; global extent.

Disadvantages

Results not easily validated in current climate.
Processes are represented by simplified relationships.



Fischer 2009

GAEZ Data: yearly yield/monthly climate; soils; crop calendars; ag systems; Spatial resolution 5'x5' lat/long

Dynamic Process Crop Models

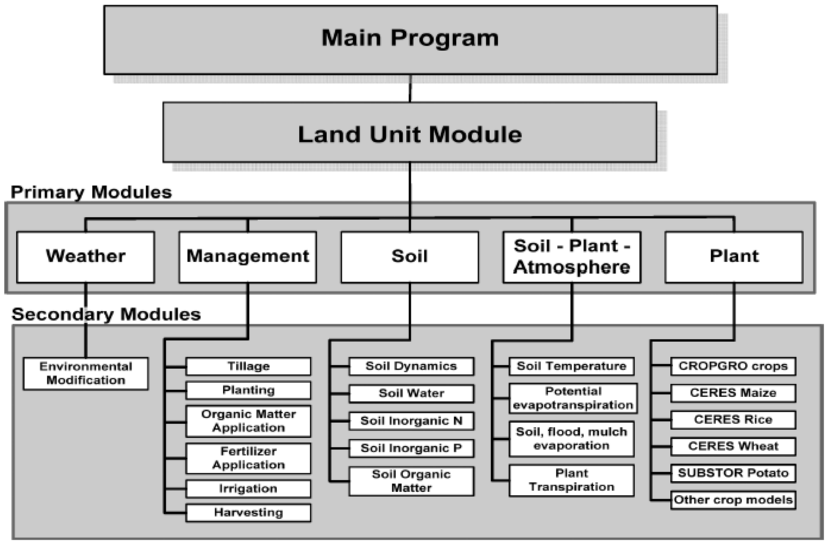
Advantages

- Explicit simulation of processes affected by climate, including CO_2 effects on growth and water use.
- Management practices included.
- Cultivar characteristics can be tested for 'design' of adapted varieties.
- Testable with experimental field data.

Disadvantages

- Not all biophysical processes included.
- Aggregation from sites to regions challenging.
- Data availability varied.

Data: daily T, P, SR; cultivar characteristics; soils, management; yearly yield
Spatial resolution: Site-based; aggregated to regions, countries



Jones 2010

Cereal Yield Response to Warming Temperate vs. Tropical Regions

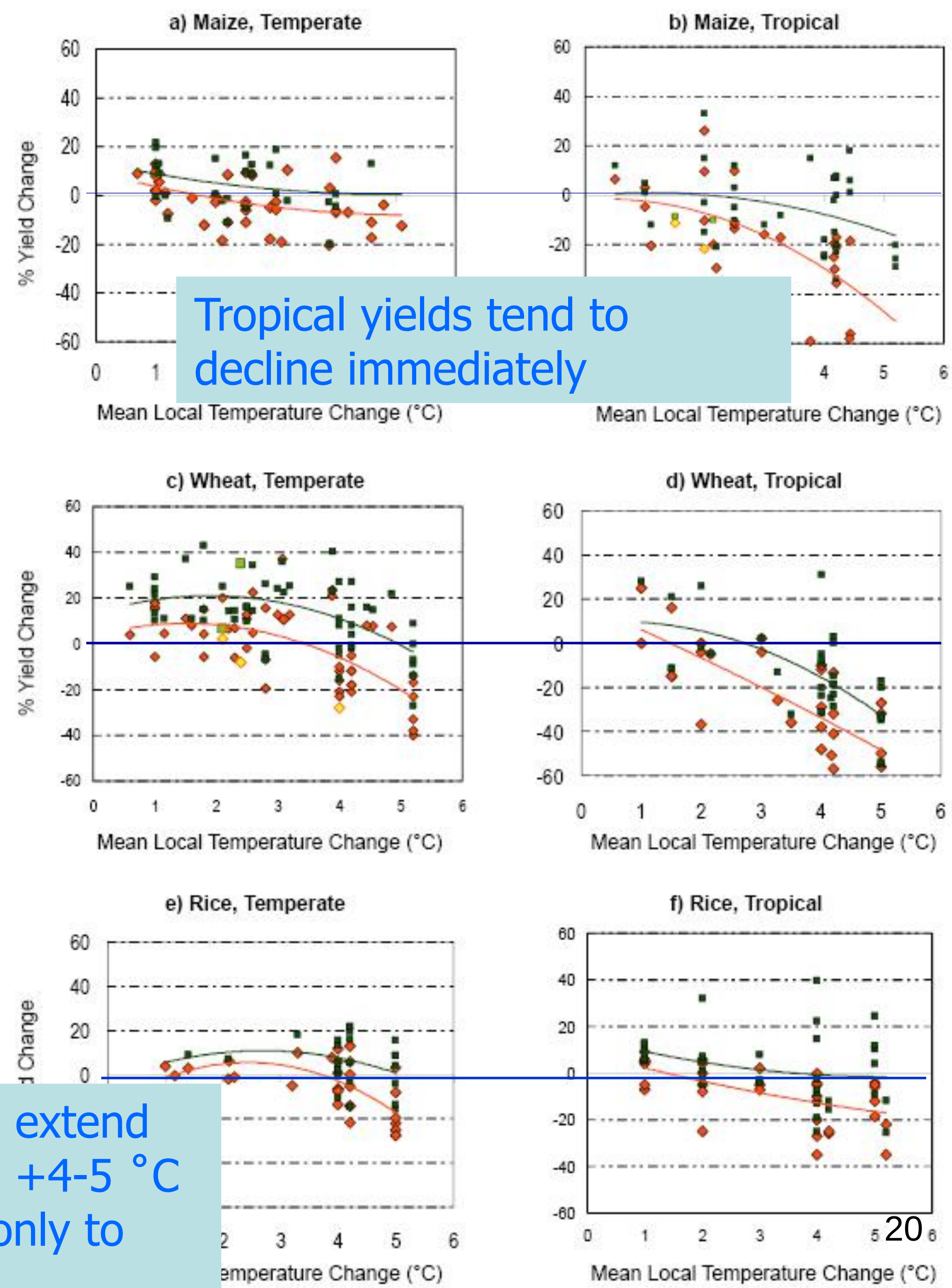
With and Without Simulated Adaptation

Temperate yields tend to thrive until +3˚C

Red = without adaptation

Green = with adaptation

—— = reference line for current yields

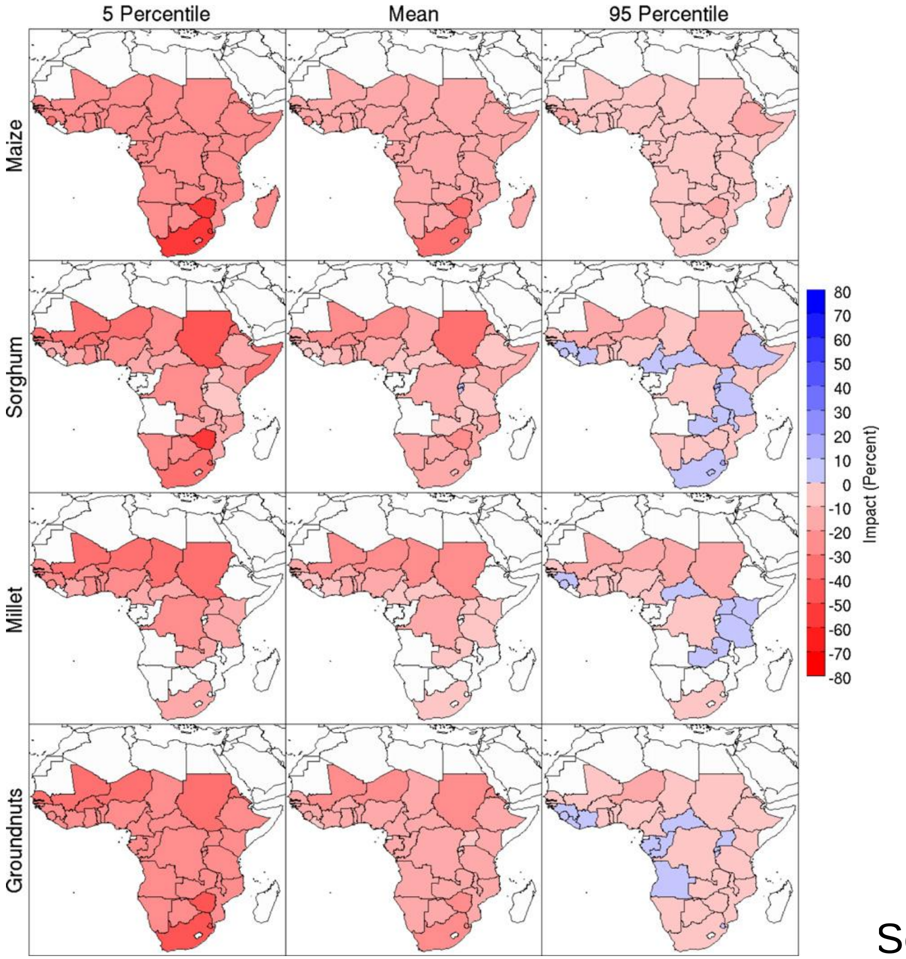


Tropical yields tend to decline immediately

Simple adaptations extend temperate crops to +4-5 ˚C but tropical yields only to +2-3˚C

IPCC, 2007

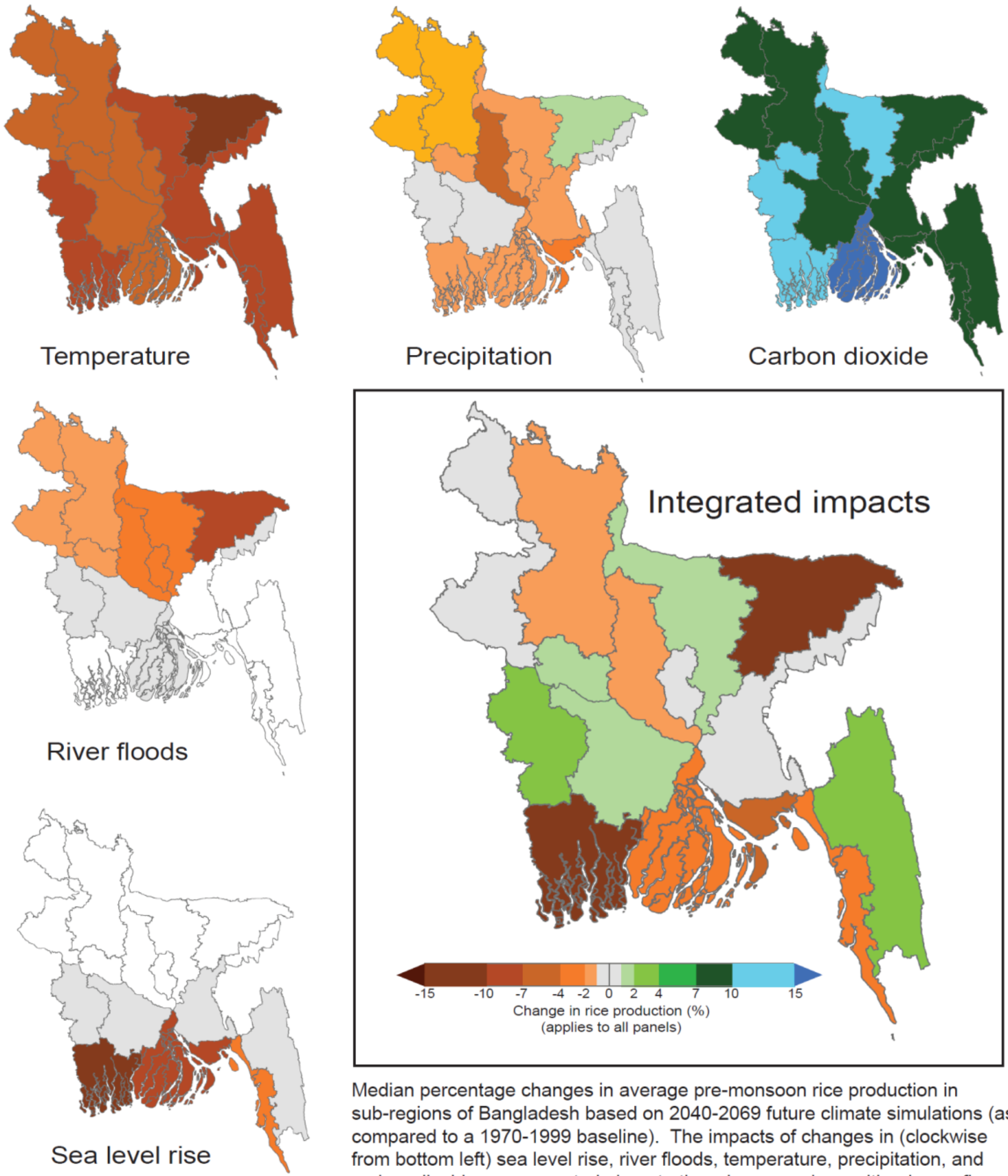
Projected Changes in Aggregate Cereal Production in Sub Saharan Africa from Climate Change in 2046-2065



- The benefits of adaptation are uncertain.
  - A portfolio of strategies are recommended
  - (e.g.) creating crops for both drought and heat tolerance
- There is a need to reduce the uncertainty in how effective different interventions are.
  - It is recommended to accelerate efforts to monitor and evaluate current activities toward adaptation.

Schlenker Lobell 2010

Projected effects of climate change factors on Bangladesh rice production in the 2050s



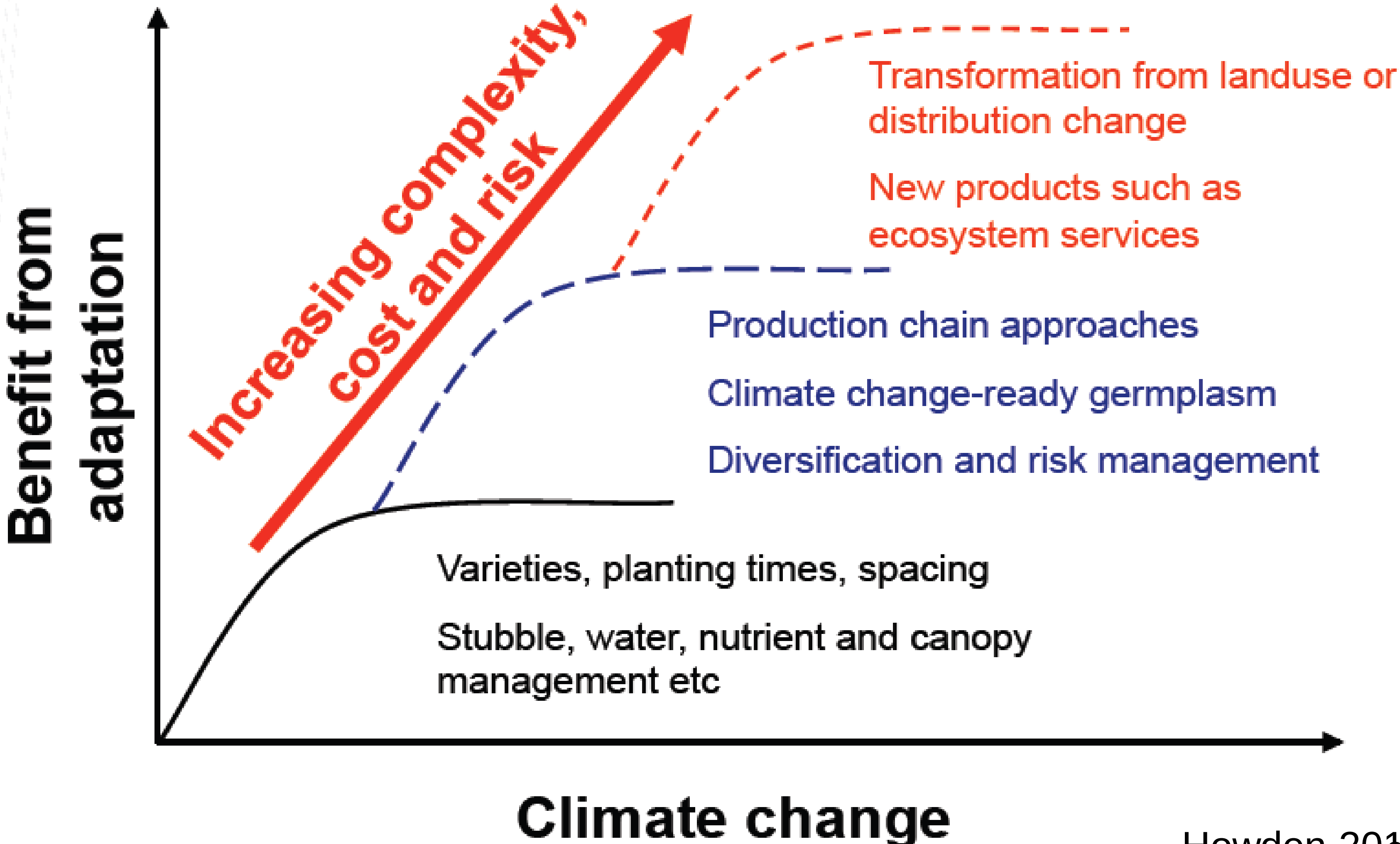
Median percentage changes in average pre-monsoon rice production in sub-regions of Bangladesh based on 2040-2069 future climate simulations (as compared to a 1970-1999 baseline). The impacts of changes in (clockwise from bottom left) sea level rise, river floods, temperature, precipitation, and carbon dioxide are presented absent other changes, along with a larger figure showing the integrated production changes when all impacts are considered.

Ruane et al., 2009; World Bank, 2009, Forthcoming

To what extent are changes in agricultural practices and technologies capable of modulating biophysical impacts?

Progressive Levels of Adaptation

Challenges and Opportunities



Howden 2010

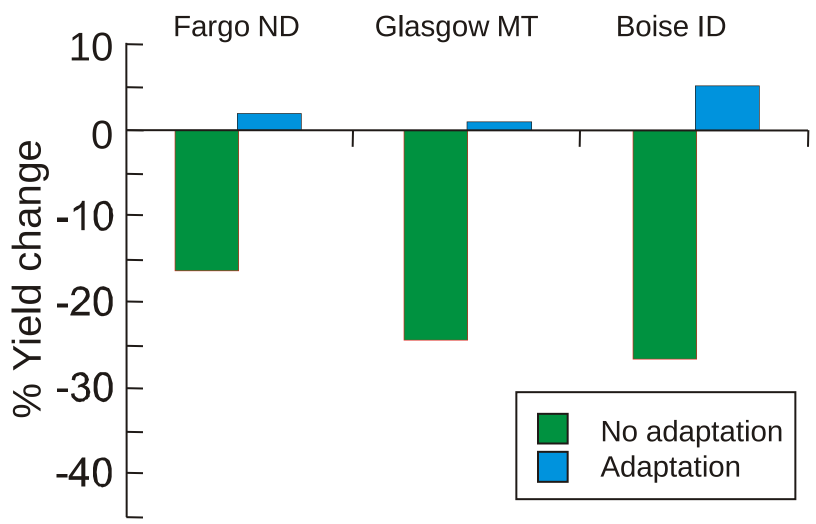
Adaptation is Not Always Possible or Complete

Two examples for the CCGS 2030s Scenario

Spring wheat

Strategy: Early planting

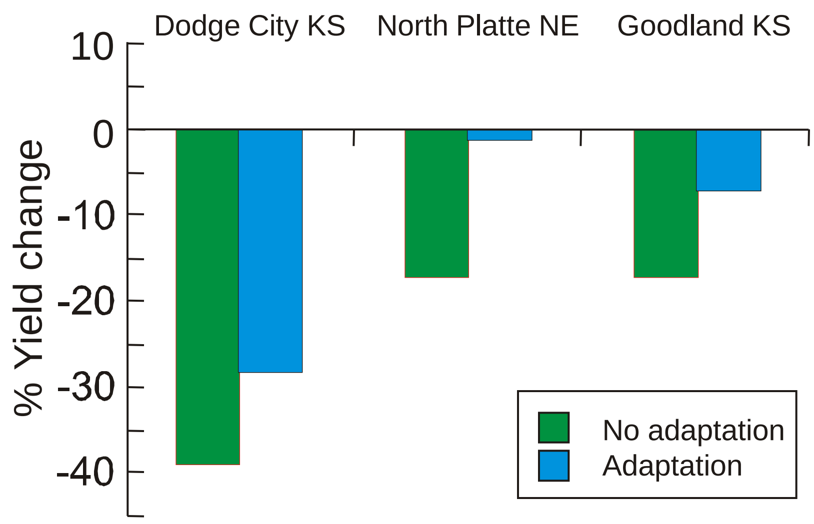
Results: Successful heat stress avoidance



Winter wheat

Strategy: Change of cultivar

Results: Unable to reverse damage due to low precipitation



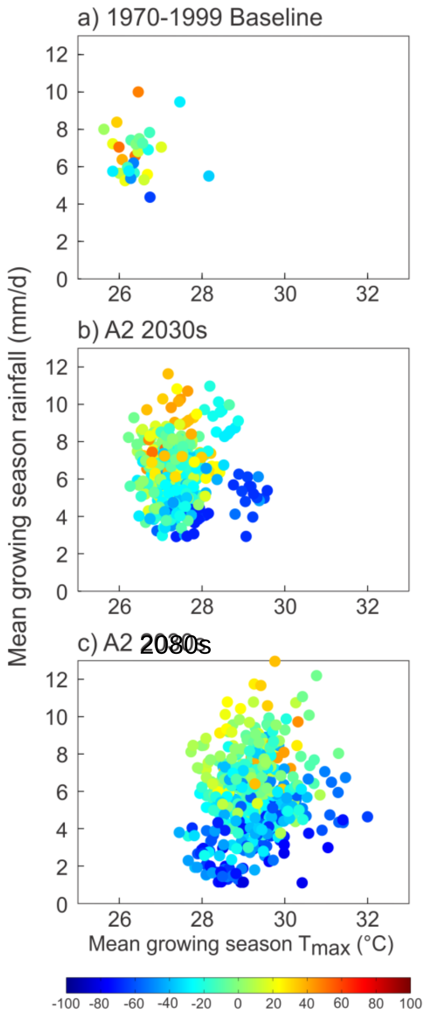
CC = Canadian Climate Centre GCM

U.S. National Assessment; Tubiello et al., 2002

What are the most important gaps or uncertainties in our knowledge regarding biophysical responses of agro-ecosystems to climate change?

What additional research would be most valuable?

Gaps and Uncertainties

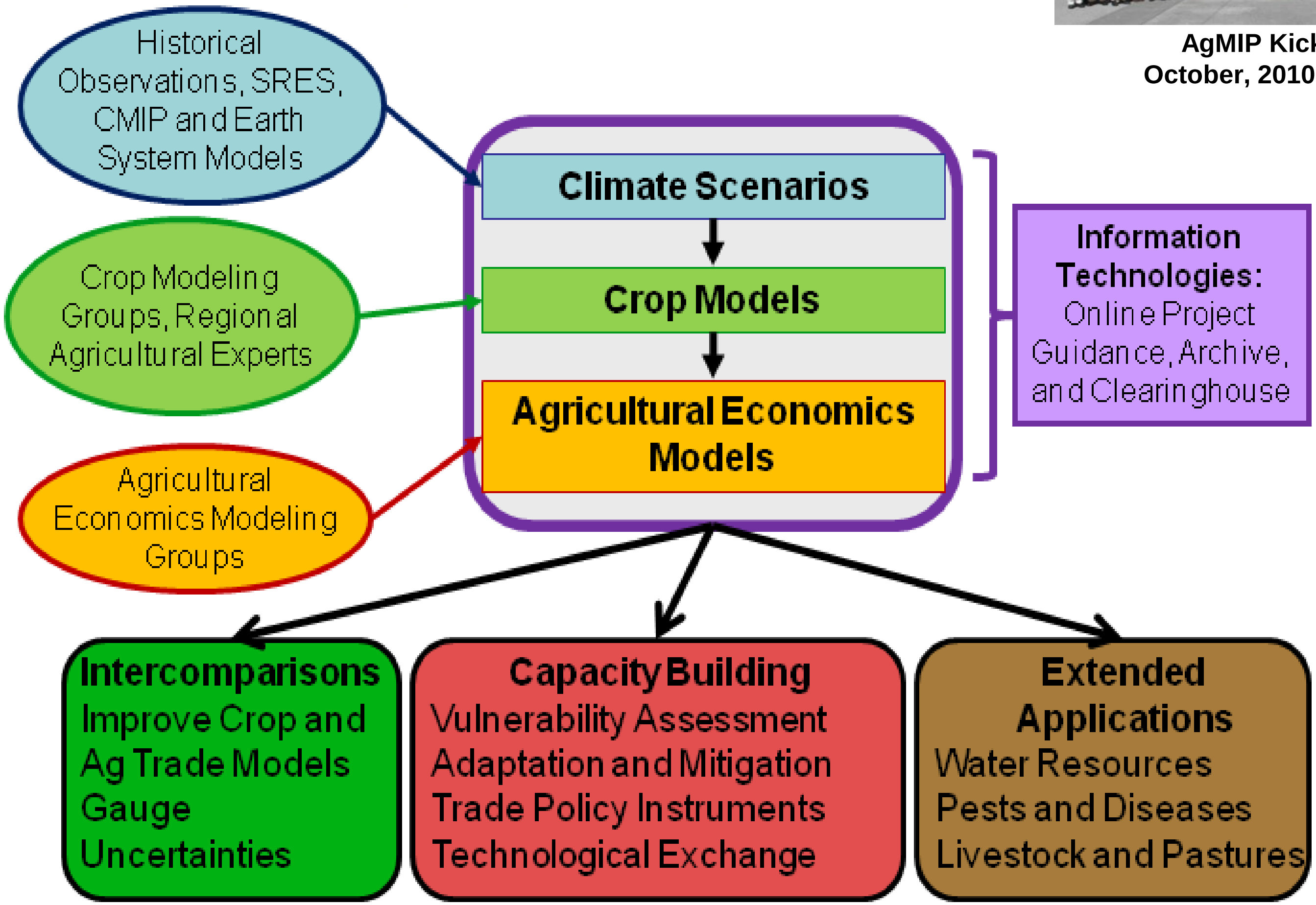


Simulated yield (as % change from 1970-1999 mean) sensitivity under constant CO_2 versus various climate metrics. Panama

- **Precipitation!**
- **Models and methods are still constrained in their ability to simulate extreme weather events.**
- **The interactions of warmer temperature with CO_2 and ozone need continued experimental research and simulation development.**
- **Effects of changes in evapotranspiration on soil moisture and crop yield and wider interactions with water availability is poorly understood.**
- **Pests**
- **Scale of simulation influences results.**
- **Yield gaps and plateaus.**
- **Lack of multi-model comparisons and assessments.**

AgMIP The Agricultural Model Intercomparison and Improvement Project

AgMIP Kickoff Workshop
October, 2010 Long Beach, CA



AgMIP components and expected outcomes

Aggregation, Uncertainty, Agricultural Pathways

Research on Climate Change Impacts and Associated Economic Damages

Wolfram Schlenker
Columbia University and NBER

For most of human history, agriculture accounted for the dominant share of GDP and employed most labor. Johnson (1997) estimates that in 1800 about 75-80% of the labor force in developed nations was engaged in farming. Before 1930, production increases were mainly driven by an expansion of the farming area while yields (output per area) remained flat. The picture flipped around 1930, when production increases switched from the extensive to the intensive margin: increases in output mainly came from increases in yields, while the total farming area remained rather constant. Yields of most commodities increased roughly threefold in the second half of the 19th century in the United States as well as other developed countries. The large increase in yields has lead to a general downward trend in agricultural prices over the 19th century. As a result, agriculture now constitutes a small share of GDP in developed countries (2-3% in the United States).

1) Why impacts on US agriculture might be economically meaningful

While agriculture is a small share of GDP, it is arguably responsible for a large amount of consumer surplus. GDP is simply the value of all produced goods and services in a country. As far back as Adam Smith, researchers have examined the paradox of “value” and asked why an essential good (water or food) can have a much lower value or price than a nonessential good (diamonds). The reason is that the price of a product is determined by its scarcity: food is currently abundant and therefore the price is low in real terms. This, however, does not mean that changes in food production have small impacts on welfare.

Demand for basic food is highly inelastic. The four basic commodities - corn, soybeans, rice, and wheat - account for roughly 75% of the calories humans consume. A demand elasticity of 0.05 for calories from these commodities implies that a 1% shortfall in production increase prices by 20%. The recent tripling of commodity prices for the basic four commodities has hardly impacted the amount of food consumed in developed countries, yet reduced global consumer surplus by roughly 1.25 trillion dollars annually (Roberts and Schlenker, 2010). Any shortfall in the production of basic food commodities has the potential for large changes in welfare.

The U.S. is by far the largest producer of basic food calories and responsible for 23% of world caloric production of the four basic commodities. Its share of basic caloric production is roughly three times as large as Saudi Arabia’s share in oil production. Any impact in the United States would have repercussions on world food markets simply due to the dominating share of US production.

2) Potential climate change impacts on US agriculture

Schlenker and Roberts (2009) use a new fine-scale weather dataset that incorporates the whole distribution of temperatures within each day and across all days in the growing season to estimate the influence of various temperatures on crop growth in a county-level panel analysis in the United States. Yields increase with temperature up to 29°C (84°F) for corn and 30°C (86°F) for soybeans. If farmers could freely choose their growing conditions, a temperature of, respectively, 84°F or 86°F every day all year long would be ideal. Both lower and higher temperatures result in suboptimal yield growth. The troublesome fact though is that the slope of the decline above the optimum is about ten times steeper than the incline below it. In other words, being 1°F above the optimum reduces yields ten times as much as being 1°F below it, or, equivalently, being 1°F above the optimum reduces yields as much as being 10°F below it. The strong relationship between temperatures above the optimum and yields implies that roughly half of the year-to-year variation in crop yields can be explained by one single measure: how often and by how much temperatures exceed the crop-specific optimum. The concept of degree days simply adds all temperatures above the optimum for each day. One day that is 10 degrees above the optimum is as harmful as 10 days that are 1 degree above the optimum. Corn futures markets confirm this highly significant relationship: futures prices for deliveries at the end of the growing season are highly sensitive to extreme heat events during the growing season, but not average temperature.

Climate change is predicted to increase the daily minimum and maximum temperatures. During the summer months, the minimum is usually below 84°F in the Midwest, the major agricultural growing area in the United States. At the same time, there are many days when the maximum temperature is above 86°F. Warming therefore has countervailing effects: shifting minimum temperatures upward closer towards the optimal growing temperature is beneficial for yields, however, shifting maximum temperatures that already exceed the optimal levels further upward decreases yields. Since the slope of the decline above the optimum is much steeper than the incline below it, the latter effect dominates, resulting in sharp net yield losses for most climate scenarios. Holding current growing regions fixed, area-weighted average yields are predicted to decrease by ~40% before the end of the century under the slowest (B1) warming scenario and decrease by ~75% under the most rapid warming scenario (A1FI) under the Hadley III model. Predicted temperature changes have larger effects that predicted precipitation changes.

Year-to-year weather fluctuations are arguably different from permanent shifts in climate. While the former are unknown at the time of planting, farmers can adapt to the latter. To examine how farmers respond to changes in average condition, one can also link *average* yields to *average* temperatures. A priori, one would have expected that areas in the Southern United States that experience temperatures above 84-86°F more frequently had an incentive to adapt to these temperatures and are hence less sensitive to extreme heat. However, the same nonlinear and asymmetric relationship is found in the time-series and cross-section. This suggests limited historical adaptation of seed varieties or management practices to warmer temperatures because the cross-section includes farmers' adaptations to warmer climates and the time-series does not. A model using farmland values instead of crop yields finds similar predicted declines if one controls for the damaging effects of extreme heat (Schlenker, Hanemann, and Fisher, 2006). Moreover, the negative coefficient on extreme heat is highly robust to various specification changes.

Similar relative sensitivities are found using a panel of yields in Africa (Schlenker and Lobell, 2010). While countries in Africa are already hotter and hence more susceptible to further temperature increases, predicted temperature increases are lower than in higher latitudes. Confidence bands on estimated yield-weather relationships are larger in Africa where both yield and weather data are measured with less precision.

3) Adaptation to climate change: evolution of heat tolerance

Given the large damaging effect of extreme heat on yields for at least two basic food commodities (corn and soybeans), the big question becomes whether technological innovation can reduce the sensitivity to these extreme temperatures. If changes in climatic conditions reduce yields, prices would rise, giving seed companies a strong incentive to innovate and make seeds more heat resistant. On the other hand, one might wonder how difficult it is from a breeding standpoint to reduce heat tolerance.

The recent past might give us some guidance: while average corn yields increased continuously in the second half of the 19^{th} century by a total factor of three, the evolution of heat sensitivity is highly nonlinear, growing with the adoption of double-cross hybrid corn in the 1940's, peaking around 1960, and then declining sharply as single-cross hybrids come online. Corn in Indiana, the state with the longest detailed daily weather record, is most sensitive to extreme temperatures at the end of the sample. Since climate change models predict an increase in extreme temperatures, the big question is whether the next breeding cycles can increase both average yields and heat tolerance simultaneously as in the period 1940-1960, or whether continued increases in average yields can only be achieved at the expense of heat tolerance as in the period from 1960 onwards. Important areas for future research are to better understand how such innovations could happen.

Genetically modified crops are the biggest hope to usher in a new era of innovation that limits a plant's sensitivity to extreme heat. To date most commercially successful genetically modified crops resist pests or herbicides. But more ambitious efforts exist to develop plants that manufacture their own nitrogen fertilizer and possess more nutrients. While public funding of basic research has diminished, private donations from charities like the Gates Foundation or by profit-driven companies like Monsanto might replace these funds. However, given public good attributes of research, there remain important questions about the extent to which private incentives to fund basic research align with potential social welfare.

4) Biofuels as mitigation option: the US ethanol mandate and food prices

Previous sections highlighted the effect of changing climatic conditions on agricultural yields. The reverse link has also received considerable attention: how does agriculture, and more specifically agricultural policies, impact climate change? Forests store a large amount of carbon, and most deforestation is done to convert forests to agricultural land. Houghton et al. (1999) estimate that 10-30 percent of fossil fuel emissions in the United States were offset by land use changes that lead to reforestation in the 1980s. By the same token, biofuel policies, especially the US ethanol mandate, have received a lot of attention as a tool to reduce CO_2 emissions and limit climate change.

Roberts and Schlenker (2010) develop a new methodology to estimate both demand and supply elasticities of agricultural commodities (maize, rice, soybeans, and wheat). While *current* weather shocks have been used to estimate demand elasticities ever since P.J. Wright introduced the concept of instrumental variables, *past* weather shocks can be used to estimate supply elasticities.

Since the estimated supply elasticity is roughly twice as large as the demand elasticity, one third of the caloric input used in biofuel production comes from reduction in food consumption while two thirds come from increases in food production. The US ethanol mandate is predicted to decrease food consumption by 1% and increase commodity prices by 20% assuming that one third of the calories used in ethanol production are recycled as feedstock for animals. Future research should examine how changes in the variance and correlation of weather shocks will impact food price spikes.

Lastly, the predicted increase in food prices due to biofuel mandates might lead to expansion of agricultural areas, which, dependent on where they occur, might result in significant increases in CO_2 emissions (Searchinger et al., 2008). This is an ongoing research area to correctly assess the effect of various mandates, e.g., the low carbon fuel standard in California.

5) References

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Estimating the Economic Impact of Climate Change in the Agricultural Sector

Wolfram Schlenker[1]

[1]Columbia University and NBER

Washington DC, January 27 2011

Outline

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Consumer Surplus

- Agriculture accounts for small share of US GDP
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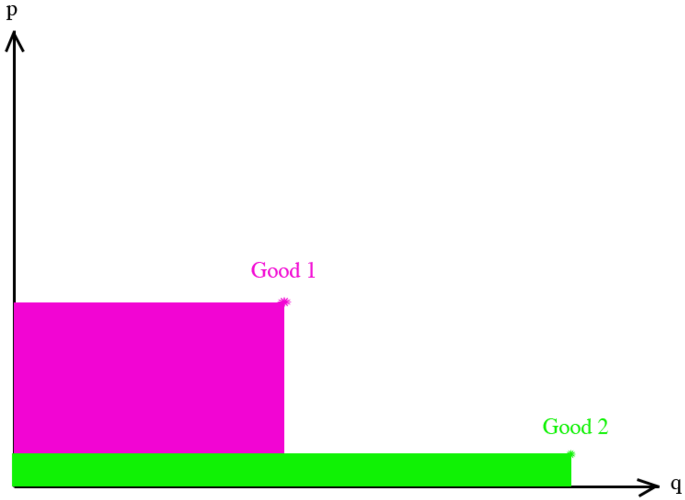

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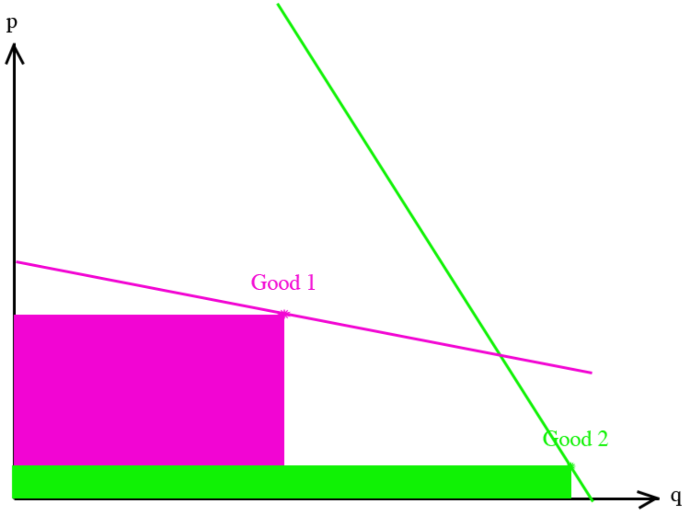

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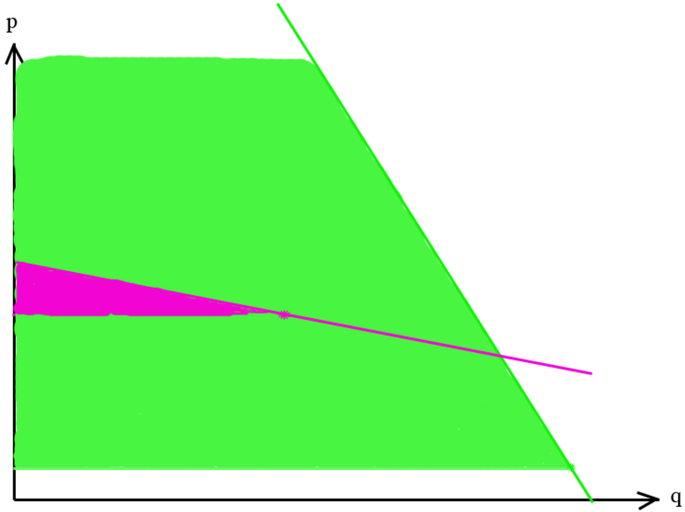

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- Climate impacts
  - Small reduction in production result in
  - Large price changes (inelastic demand)
  - Potential for large welfare losses (consumer surplus)

Agriculture in US

- Four basic staple commodities
  - Corn, rice, soybeans, and wheat
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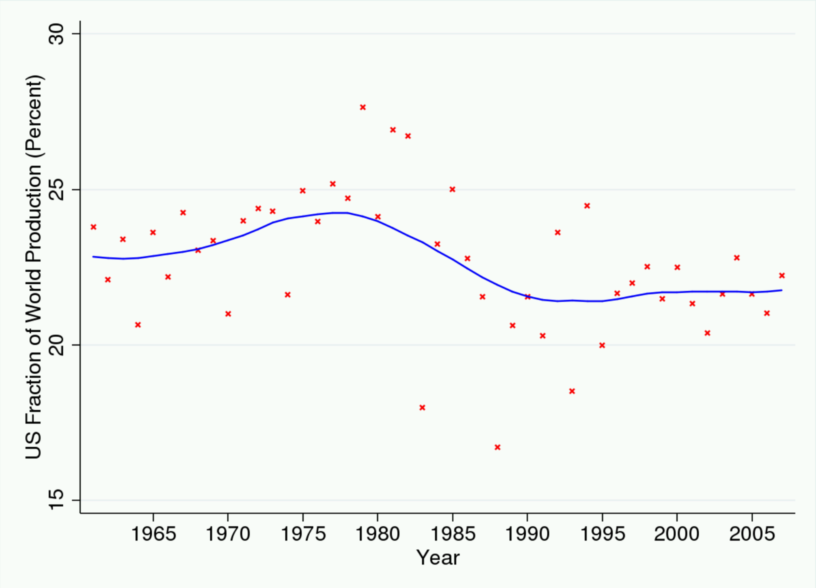
- US share of caloric production
  - Roughly constant around 23% (last 50 years)
  - Larger than Saudi Arabia's share of oil production
  - Impacts on US yields have potential to influence world markets

Agriculture in US



Outline

1. Why Impacts on US Agriculture Might be Economically Meaningful
2. Potential Impacts of Climate Change on US Agriculture
3. Technological Progress: Evolution of Heat Tolerance
4. Agriculture's Role in Fighting Global Warming
5. Conclusions

Link between Temperature and Yields

- Statistical Analysis
  - Panel of county-level yields in Eastern United States
  - Corn and Soybeans (two biggest staple commodities in US)
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  - State-specific quadratic time trends
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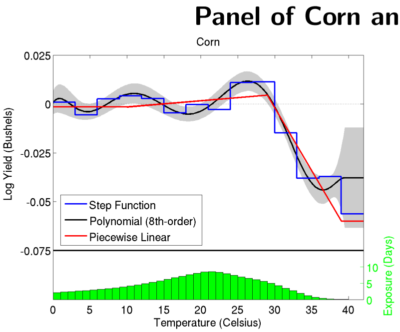

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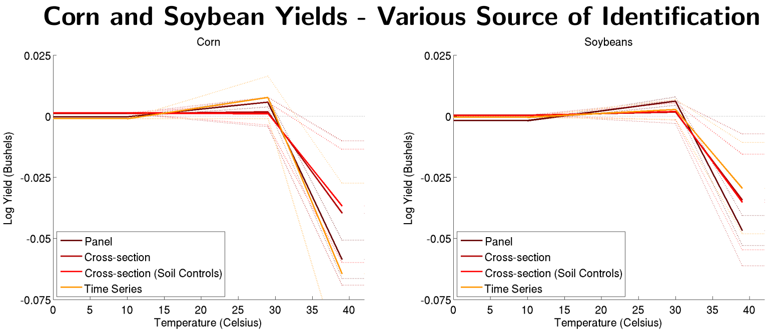

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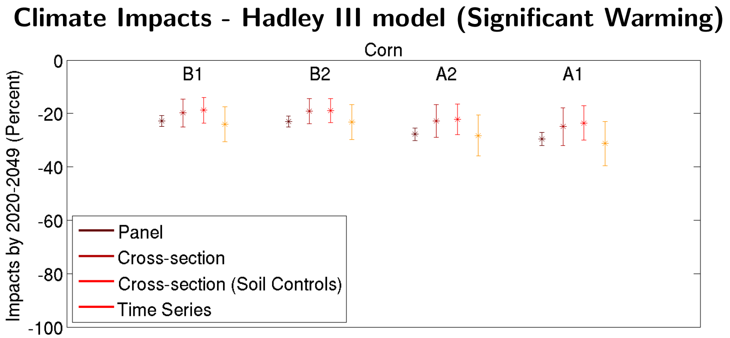
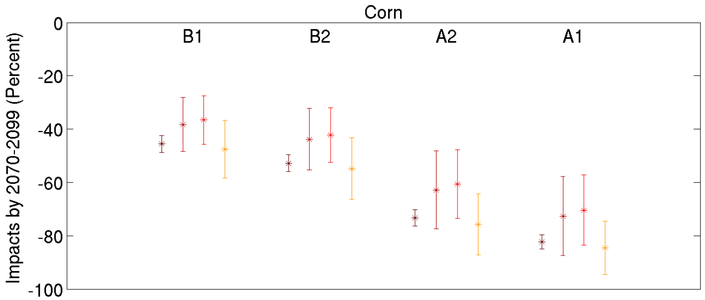


Link between Temperature and Yields

Climate Impacts - Hadley III model (Significant Warming)

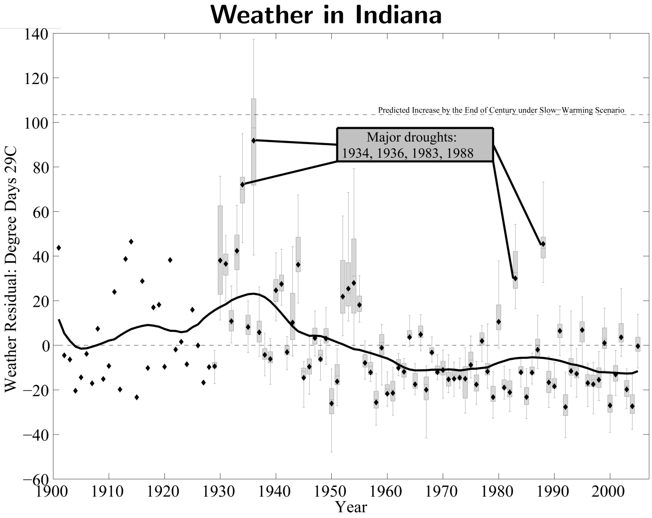


Link between Temperature and Yields

- Other parts of globe
  - Tropics: hotter baseline but lower temperature increases
- Can crop switching save the day?
- Cross-sectional analysis of farmland values
  - Accounting for extreme heat
  - Limit to Eastern United States
- Similar results
  - Large negative effect of extreme heat
  - Robust to myriad of specification checks
    - Different census years
    - Permutations of other control variables

Outline

Evolution over Time



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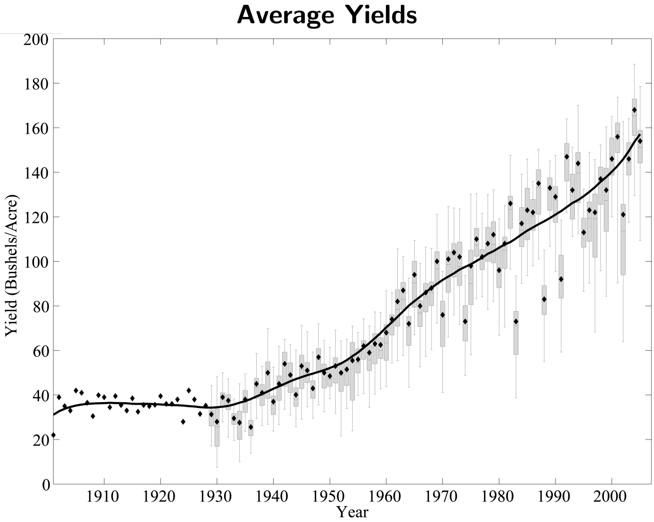

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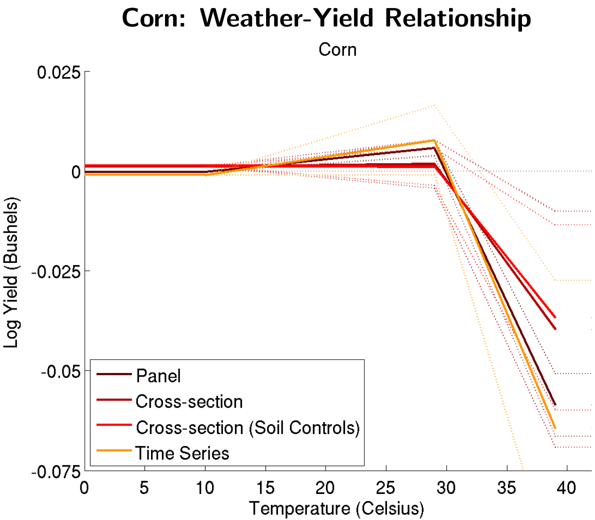

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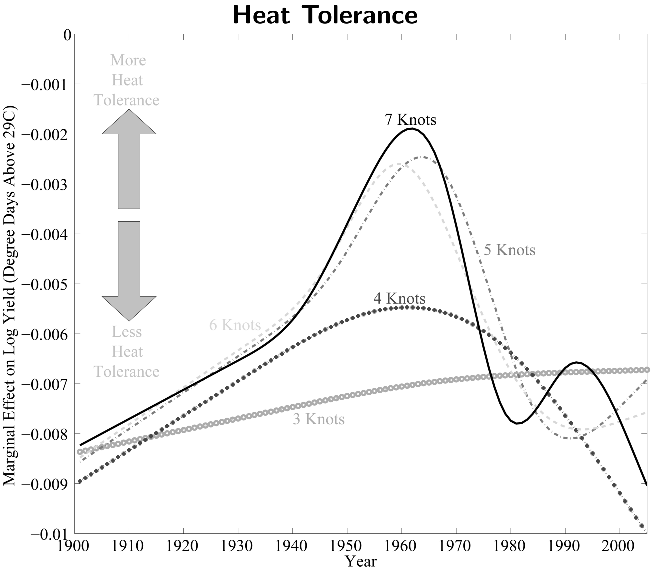

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Agriculture and CO2 Emissions

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- Concern: Indirect land use change / food prices
  - 2009 Renewable Energy Standard
  - 5% of world caloric production of 4 basic staples go into biofuels
  - Predicted commodity price increase 20% (one third recycling ratio)
    - Reduces consumer surplus by 150billion annually
  - Supply mainly from extensive margin
    - Indirect land use change impacts CO_2 balance

Agriculture and CO2 Emissions

- Price increase / indirect land use change
  - Depends on demand and supply elasticity for calories
- Study identifying demand / supply elasticities
  - Demand: global yield shocks
  - Supply: lagged yield shocks
- Data
  - Yearly country level yield shocks
  - Combine 4 basic staples (corn, rice, soybeans, and wheat)
  - Futures price data (Chicago Board of Trade)

Agriculture and CO2 Emissions

	Model					
	2SLS	3SLS	2SLS	3SLS	2SLS	3SLS
	Demand and Supply Elasticities					
β_d	-0.0505***	-0.0554***	-0.0641**	-0.0797***	-0.0668***	-0.0634***
(s.e.)	(0.0190)	(0.0167)	(0.0243)	(0.0215)	(0.0241)	(0.0226)
β_s	0.1165***	0.1337***	0.0826***	0.0951***	0.0957***	0.0979***
(s.e.)	(0.0286)	(0.0241)	(0.0217)	(0.0189)	(0.0208)	(0.0189)
Δp	31.41	27.01	36.10	29.31	32.14	32.16
(95%)	(21.32,50.14)	(20.69,36.62)	(23.75,60.31)	(22.01,40.80)	(22.23,50.00)	(22.79,48.40)
N	42	42	42	42	41	41
I	2	2	3	3	3	3
K	1	1	1	1	2	2

β_d Demand elasticity
β_s Supply elasticity
Δp Predicted price increase (0% recycling as feed stock)

Outline

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  - Average yields have risen steadily since 1940
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- Ethanol mandate
  - Requires 5% of caloric production (4 basic staples)
  - Predicted to increase commodity prices by 20%
  - Indirect land use change

References

Papers with more detail available:
www.columbia.edu/∼ws2162

Climate-Associated Changes in Health Outcomes

Kristie L. Ebi, Ph.D., MPH
Carnegie Institution for Science

Introduction

Climate change has the potential to affect any health outcome that is seasonal or that is associated with weather and climate. In addition, many key determinants of human health, such as food and freshwater availability, are strongly influenced by weather and climate. Climate-sensitive health outcomes include injuries, illnesses, and deaths associated with extreme weather events, and the effects of changing weather patterns mediated through ecological systems, such as water- and food-borne diseases, vectorborne and zoonotic diseases, respiratory diseases associated with ground-level ozone and aeroallergens, and undernutrition. Climate change also may result in resource depletion and other processes that could lead to large-scale migration, with associated health impacts. While negative health effects are projected for all countries, the largest impacts are expected in lower-income populations, primarily those living in tropical and subtropical countries.

Health Risks of Climate Change

Infectious Diseases

Climate is a primary determinant of whether a particular location has environmental conditions suitable for the transmission of a range of infectious diseases. Increasing temperatures could affect vector and rodent borne diseases, in terms of the density of insects and rodents in a particular area (and therefore the likelihood of infection) and by changing the geographic range of the vector and pathogen. Expansion in range can expose new populations who have little or no immunity to new infections, which could result in large disease outbreaks. Although understanding of the potential impacts of climate change on infectious diseases is still in its relatively early stages, expert assessments have concluded that climate change is expected to be among the most important drivers of infectious disease in the future.[i] A UK review considered scenarios for the next 10-25 years of infectious diseases in humans, animals, and plants for the UK and sub-Saharan Africa, and aimed to produce a vision of new systems needed for disease detection, identification and monitoring. The key driver in the UK was expected to be increasing ambient temperature. In Africa, where people, animals and crops live in conditions of much greater moisture stress, rising temperature were still considered to be important but less so than changes to rainfall patterns and the frequency of droughts. Climate-change mediated spread of infectious diseases was expected to cause direct human suffering, especially in Africa, and increasingly challenge current production systems of livestock and crops in the UK and Africa.

Malaria is the most important vectorborne disease in the world; it is also a preventable disease. About 40% of the world's population is at risk of contracting malaria, and roughly 75% of cases occur in Africa, with the remainder occurring in Southeast Asia, the western Pacific, and the Americas.[ii] In sub-Saharan Africa, malaria remains the most common parasitic disease and is the main cause of morbidity and mortality among children less than five years of age and among pregnant women.[iii] The 1990 Global Burden of Disease study estimated that malaria accounted for approximately 10.8% of years of life lost across sub-Saharan Africa.[iv]

There has been a great deal of interest in modeling how the incidence and geographic range of malaria could change under different climate change projections. Results from several models suggest that climate change could alter the season of transmission and geographic range of malaria in Africa, particularly sub-Saharan Africa.[v] The results suggest that climate change will be associated with geographic expansions of the areas suitable for stable *falciparum* malaria in some regions and with contractions in others; the projected areas of expansion are larger than the projected areas of contraction. For instance, Ethiopia, Zimbabwe, and South Africa are projected to show increases of more than 100% in person-months of exposure later in this century, changes that could dramatically increase the burden of those suffering with malaria.[vi]

Studies have shown that some areas in Asia are projected to be at increased risk of malaria, while reductions have been projected for some areas in Central America and around the Amazon, due to decreases in rainfall.[vii] An assessment in Australia based on climatic suitability for the main *Anopheline* vectors projected a likely southward expansion of habitat, although the future risk of endemicity would remain low due to the capacity to respond.[viii]

Climate change could affect the incidence and geographic range of a large number of vectorborne and zoonotic diseases of concern include dengue fever, Lyme disease, plague, Chagas disease, Rift valley fever, and leishmaniasis; expansions and contractions of ranges are possible as ecosystems and transmission pathways change with changing weather patterns.[ix]

Several food- and waterborne diseases that cause significant numbers of cases of illness are climate sensitive, suggesting that climate change may affect their incidence and distribution. For example, an approximately linear association between temperature and common forms of food-borne diseases such as salmonellosis suggests increasing cases with increasing temperature.[x] Limited projections suggest these risks could increase with climate change.[xi]

Air Pollution

In some regions, climate change may increase concentrations of selected air pollutants, particularly ozone, and could decrease concentration of other pollutants, such as particulate matter (due to increasing heavy precipitation events). There is extensive literature documenting the adverse health impacts of exposure to elevated concentrations of air pollutants. In 2000, there were 800,000 deaths from respiratory problems, lung disease, and cancer that were attributed to urban air pollution, with the largest burden in low-income countries in the Western Pacific and South East Asia.[xii] In addition, there were 1.6 million deaths attributed to indoor air pollution caused by burning biomass fuels, such as wood and dung.

More is known about the potential impacts of climate change on ground-level ozone than on other air pollutants. Acute exposure to elevated concentrations of ozone is associated with increased hospital admissions for pneumonia, chronic obstructive pulmonary disease, asthma, allergic rhinitis and other respiratory diseases, and with premature mortality.[xiii]

Changes in concentrations of ground-level ozone driven by scenarios of future emissions and /or weather patterns have been projected for Europe and North America, with most projections suggesting increasing concentrations.[xiv] [xv] Higher ozone concentrations will likely increase a range of health problems and increase premature mortality in susceptible individuals.[xvi] Despite the heavier pollution burdens, no studies have been conducted for cities in low- or middle-income countries.

Malnutrition

Climate change threatens human health through its effect on under-nutrition and food insecurity. More than 800 million people are undernourished, causing over 15% of the total global disease burden, and over three billion people are micronutrient deficient.[xvii] The prevalence of undernourishment has fallen over recent decades, with reductions in Asia and Latin America partly offset by increases in Africa and the Middle East. Almost 60% of the world's undernourished people live in South Asia, while the highest incidence of undernourishment is in Sub-Saharan Africa, where more than one-third of the population is underfed.

Recent projections suggest that half of the world's population could face severe food shortages by the end of the century as rising temperatures take their toll on farmers' crops; a greater proportion of this will be in Africa.[xviii] Harvests of staple food crops such as rice and maize could fall by between 20% and 40% as a result of higher temperatures during the growing season in the tropics and sub-tropics. Although data are limited, malnutrition associated with drought and flooding may be one of the most important consequences of climate change due to the large number of people that may be affected.[xix]

Extreme Weather Events

The adverse health consequences of flooding and windstorms often are complex and far-reaching, and include the physical health effects experienced during the event or clean-up process, effects brought about by damage to infrastructure related to water supply, sanitation, and drainage, and population displacement.[xx] Extreme weather events are also associated with mental health effects, such as post-traumatic stress disorder, resulting from the experience of the event or from the recovery process. These psychological effects tend to be much longer lasting and may be worse than the direct physical effects.[xxi] More than 90% of the disasters that occurred in 2007 were the result of extreme weather- or climate-related events, together accounting for 95% of the reported fatalities and 80% of the total USD82 billion economic losses. The health impacts of extreme events in low- and middle-income countries are substantially larger.

Heat waves affect human health via heat stress, heatstroke, and death,[xxii] as well as exacerbating underlying conditions that can lead to an increase in mortality from all causes of death.[xxiii] Older adults, children, city-dwellers, the poor, and people taking certain medications are at the highest risk during a heat wave. The numbers of heat-related deaths are projected to increase with climate change.[xxiv]

Projections suggest that regions affected by moderate droughts are set to double by the end of the century, with areas affected by extreme droughts increasing from 1% today to 30% in 2100. The most striking impact is expected in parts of southern Europe, North, West and Southern Africa, western Eurasia, and the US. The loss of livelihoods due to drought is a major trigger for population movements that may cause additional adverse health burdens. The effects of drought on health include malnutrition (protein-energy malnutrition and/or micronutrient deficiencies), infectious and diarrheal diseases, and respiratory diseases.[xxv] Droughts, especially in rural areas, have a tendency to influence migration into cities, increasing urbanization and stressing the socio-economic conditions already affected by high levels of city population growth.

Prolonged droughts fuel fires, releasing respiratory pollutants, while floods can create mosquito breeding sites, foster fungal growth, and flush microbes, nutrients and chemicals into bays and estuaries, causing water-borne disease outbreaks from organisms like *E. coli* and cryptosporidium.[xxvi]

Global Assessments of the Health Impacts of Climate Change

The most comprehensive evaluation of the health burden due to climate change used a comparative risk assessment approach to estimate total health burdens from climate change in 2000 and 2030, and to project how much of this burden might be avoided by stabilizing greenhouse gas (GHG) emission.[xxvii] The health outcomes (diarrhoea, malaria, malnutrition, heat-related mortality, and injury from floods and landslides) were chosen based on sensitivity to climate variations, likely future importance, and availability of quantitative global models (or the feasibility of constructing them). The projected relative risks attributable to climate change in 2030 vary by health outcome and region, and are largely negative, with the majority of the projected health burden due to increases in diarrheal disease and malnutrition, primarily in low-income populations already experiencing a large burden of disease. The study is described in more detail in the Annex.

These results are consistent with a review that concluded that health risks are likely to increase with increasing global mean surface temperature, particularly in low latitude countries.[xxviii] Actual health burdens depend on assumptions of population growth, future baseline disease incidence, and the extent of adaptation.

Research Needs

A recent cross-agency working group in the U.S. summarized the research needs for better understanding of the linkages between climate change and health.[xxix] Overarching themes include focusing on systems and complexity, enhancing risk communication and public health education, co-benefits of mitigation and adaptation strategies, and urgency and scope

- Improve characterization of exposure- response relationships, particularly at regional and local levels, including identifying thresholds and particularly vulnerable groups. This needs to be done within the context of complex systems.
- Collect data on the early effects of changing weather patterns on climate-sensitive health outcomes.
- Collect and enhance long-term surveillance data on health issues of potential

concern, including vectorborne and zoonotic diseases, air quality, pollen and mold counts, reporting of food- and water-borne diseases, morbidity due to temperature extremes, and mental health impacts from extreme weather events.

- Develop quantitative models of possible health impacts of climate change that can be used to explore the consequences of a range of socioeconomic and climate scenarios.
- Understand local- and regional-scale vulnerability and adaptive capacity to characterize the potential risks and the time horizon over which climate risks might arise.
- Develop downscaled climate projections at the local and regional scale in order to conduct the types of vulnerability and adaptation assessments that will enable adequate response to climate change, and to determine the potential for interactions between climate and other risk factors, including societal, environmental, and economic.
- Improve understanding of designing, implementing, and monitoring effective and efficient adaptation options.
- Understand the co-benefits of mitigation and adaptation strategies.
- Enhance risk communication and public health education.

ANNEX

Estimating Current and Future Population Health Burdens Attributable to Climate Change: the WHO Global Burden of Disease Study

The first global estimate of current and possible future population health burdens attributable to climate change was conducted as part of the World Health Organization's *Global Burden of Disease (2000)* project (McMichael et al. 2004). This study remains the most comprehensive projection of the health impacts of climate change.

The Global Burden of Disease study used published information on climate-health (exposure-effect) relationships to estimate the proportion of the actually observed cases of a specified disease (e.g., malaria or child diarrhea) that could be reasonably attributable to climate change. The steps to estimate the current attributable burden of disease and premature death were:

(i) Determine or estimate changes in temperature (and other climate variables) over the recent past.

(ii) Determine (to the extent possible given data limitations), for each disease of interest, the current rates of incidence or premature death, by geographic region.

(iii) Determine from the published scientific literature, for each disease of interest, the increase in disease risk per unit increase in temperature or other climate variable (i.e. the relative risk).

(iv) Apply the relative risk to the existing rates of disease or death to estimate the 'population attributable fraction' (assuming all persons are equally exposed to the change in climate).

Estimation of the attributable burden of disease and premature death was limited to malaria, malnutrition, diarrheal disease, and floods, plus, as a minor contribution, the impacts of heatwaves. It is important to note that this study was conservative because it was limited to those health outcomes for which the baseline climate-health relationship had already been reasonably well characterized in the literature. Also, cautious assumptions were made that the health risks would be significantly reduced with economic development.

The same method was used to estimate the future burden of disease and premature death attributable to climate change for the year 2030. This requires, for a specified future time:

- A modeled scenario of global climate change, geospatially differentiated at the appropriate scale.
- Estimations, by region/country, of population size, and age structure.
- Estimations, by region/country, of the future baseline (counter-factual) rates of disease incidence or premature death.
- Assumptions about the applicable relative risk (e.g. does it stay constant, increase, or decrease over time, given that there will be changes in the target population, including changes due to adaptive actions).

2030 was chosen as the time horizon because, among other reasons, beyond a few decades into the future, there is increasing uncertainty about trends in social, economic, and political circumstances, population living conditions, and the background population health profile.

Study Details

The World Health Organization (WHO) Global Burden of Disease study began in 1992 with the objective of quantifying the burden of disease and injury in human populations (Murray and Lopez 1996). The burden of disease refers to the total amount of premature death and morbidity within a population. The goals of the study were to produce the best possible evidence-based description of population health, the causes of lost health, and likely future trends in health in order to inform policy-making. The WHO Global Burden of Disease 2000 project (GBD) updated the earlier study (Murray et al. 2002). It drew on a wide variety of data sources to develop internally consistent estimates of incidence, prevalence, and mortality, and severity and duration, for over 130 major health outcomes, for the year 2000 and beyond.

To the extent possible, the GBD synthesized all relevant epidemiologic evidence on population health within a consistent and comprehensive framework, the comparative risk assessment. Twenty-six risk factors were assessed, including major environmental, occupational, behavioral, and lifestyle risk factors. Climate change was one of the environmental risk factors assessed (McMichael et al. 2004).

The GBD used two summary measures of population health, mortality and the Disability Adjusted Life Years lost (DALYs) (Murray and Lopez 1996). DALYs provide a better measure than mortality of the population health impacts of diarrheal diseases, malnutrition, and malaria. The attributable burden of DALYs for a specific risk factor was determined by estimation of the burden of specific diseases related to the risk factor; estimation of the increase in risk for each disease per unit increase in exposure to the risk factor; and estimation of the current population distribution of exposure, or future distribution as estimated by modeling exposure scenarios.

For climate change, the questions addressed were what would be the total health impact caused by climate change between 2000 and 2030, and how much of this burden could be avoided by stabilizing greenhouse gas emissions (McMichael et al. 2004). The alternative exposure scenarios were:

- Unmitigated emission trends (UE) (i.e. approximately following the IPCC IS92a scenario);
- Emissions reductions resulting in stabilization at 750 ppm CO_2-equivalent by 2210 (s750); and
- Emissions reductions resulting in stabilization at 550 ppm CO_2-equivalent by 2170 (s550).

Climate change projections were generated using the HadCM2 global climate model (Johns et al. 2001). The health outcomes included were chosen based on sensitivity to climate variation, predicted future importance, and availability of quantitative global models (or feasibility of constructing them); these were:

- the direct health impacts of heat and cold,
- episodes of diarrheal disease,
- cases of *Plasmodium falciparum* malaria,
- fatal unintentional injuries in coastal floods and inland floods/landslides, and
- estimated prevalence of malnutrition (indicated by non-availability of recommended daily calorie intake).

Both global and WHO region-specific estimates were generated.

Results From the WHO Global Burden of Disease Project

Table 1 summarizes the health outcomes included, as well as the assumed mechanism by which climate change induces each of the specified health outcomes.

Table 1: Health Outcomes Included in the WHO Global Burden of Disease Project

Class	Mechanism	Outcome
Direct impacts of heat and cold:	Thermal stress due to higher temperatures	Cardiovascular disease deaths
Water-washed, waterborne, and foodborne disease:	Higher temperatures encourage proliferation of bacterial pathogens	Diarrhoea episodes
Vector-borne disease:	Rainfall and temperature affect vector abundance. Temperature affects incubation period of parasite in mosquito	Malaria cases
	Temperature affects incubation period of virus in mosquito	Dengue cases
Natural disasters*:	Increased floods and landslides due to sea level rise and extreme rainfall.	deaths due to unintentional injuries other unintentional injuries (non-fatal)
Risk of malnutrition	Changes in food production and per capita food availability.	non-availability of recommended daily calorie intake

Source: McMichael et al. 2004

For the year 2000, the mortality attributable to climate change was estimated to be 154,000 (0.3%) deaths, and the attributable burden was 5.5 million (0.4%) DALYs, with approximately 50% of the burden due to malnutrition (McMichael et al. 2004). These estimates are for the year 2000, by which time the amount of climate change since the selected baseline year (1990) was small (approximately 0.2^{o}C). Therefore, future disease burdens would be expected to increase with increasing climate change, unless (implausibly) fully effective adaptation measures were implemented.

Approximately 46% of the DALYs attributable to climate change were estimated to have occurred in the WHO South-East Asia Region (which includes South Asia), 23% in countries in the Africa region with high child mortality and very high adult male mortality, and 14% in countries in the Eastern Mediterranean region with high child and adult male mortality.

Table 2 summarizes the estimated numbers of deaths occurring in 2000 as a result of the impacts of climate change on the occurrence of the five specified health outcomes amenable to quantitative modeling (see Annex 2 for WHO regions). Figure 3 maps these results by WHO region.

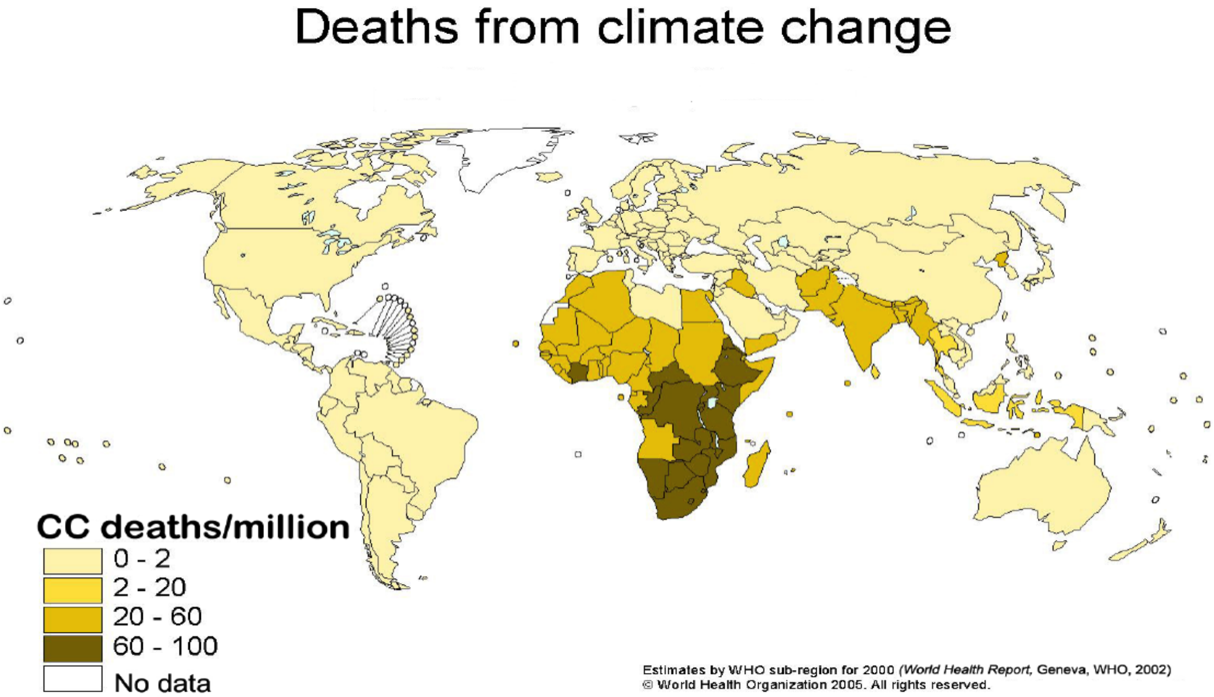
Table 2: Estimated mortality (000s) attributable to climate change in the year 2000, by cause and WHO region

Table 20.16 Estimated mortality (000s) attributable to climate change in the year 2000, by cause and subregion

Subregion	*Malnutrition*	*Diarrhoea*	*Malaria*	*Floods*	*CVD*	*All causes*	*Total deaths/million population*
AFR-D	8	5	5	0	1	19	66.83
AFR-E	9	8	18	0	1	36	109.40
AMR-A	0	0	0	0	0	0	0.15
AMR-B	0	0	0	1	1	2	3.74
AMR-D	0	1	0	0	0	1	10.28
EMR-B	0	0	0	0	0	1	5.65
EMR-D	9	8	3	1	1	21	61.30
EUR-A	0	0	0	0	0	0	0.07
EUR-B	0	0	0	0	0	0	1.04
EUR-C	0	0	0	0	0	0	0.29
SEAR-B	0	1	0	0	1	2	7.91
SEAR-D	52	22	0	0	7	80	65.79
WPR-A	0	0	0	0	0	0	0.09
WPR-B	0	2	1	0	0	3	2.16
World	77	47	27	2	12	166	27.82

CVD Cardiovascular disease. As described in section 3.6, the estimated cardiovascular deaths represent temperature-related mortality displacement. Therefore no disease burden is estimated for deaths from this cause in Table 20.17.

Figure 3: Burden of Premature Deaths Attributable to Climate Change, for Year 2000



Estimates of Climate Change-Related Cases of Diarrheal Diseases, Malnutrition, and Malaria in 2030

The WHO GBD study used the calculated relative risks to estimate the excess number of incident cases of diarrheal diseases, malnutrition, and malaria in 2030 for the three scenarios (unmitigated emissions (UE) and stabilization scenarios at 550 and 750 ppm CO_2-equivalent).

Diarrheal Diseases

For the estimations for diarrheal diseases, developing countries were defined as those with per capita incomes less than US$6,000/year in 1990 US dollars. For such countries, the exposure-response relationship used was a 5% increase in diarrheal incidence per ºC increase in temperature; this estimate was based on two studies (Checkley et al. 2000; Singh et al. 2001). The study assumed that the climate sensitivity of diarrhea would decrease with increasing GDP; once a country was projected to reach per capita incomes of UD$6,000/year, then overall diarrhea incidence was assumed to not respond to changes in temperature. The study assumed that diarrheal incidence in richer countries is insensitive to climate change.

The relative risks for each region are a population-weighted average of the countries within the region. The model output was used to generate mid-range estimates; the high relative risks were calculated as a doubling of the mid-range estimate.

Malnutrition

Estimates of national food availability were based on the effects of temperature and precipitation, and the beneficial effects of higher CO_2 levels, projected using the

IBSNAT-ICASA dynamic crop growth models (IBSNAT 1989). Principal characteristics of this model include:

- No major changes in the political or economic context of world food trade or in food production technology;
- Demographic change follows the World Bank mid-range estimate (i.e. 10.7 billion by the 2080s);
- GDP to accumulate as projected by EMF14 (Energy Modeling Forum 1995); and
- A 50% trade liberalization in agriculture is introduced gradually by 2020.

Note that malnutrition has multiple causes. Access to a range of affordable quality foods is required for adequate nutrition. There may be sufficient food production within a country, but families may not have access because the food is not culturally desirable, it is too expensive, or there is inadequate transportation. Subsistence farmers and the urban poor are particularly at risk. Therefore, economic and political factors can be as important as climate in determining food availability. However, this model focused only on the association between climatic factors (including CO_2) and national food availability.

Analyses suggested that the model output was positively related to more direct measures of malnutrition, including incidence of underweight, stunting, and wasting in children <5 years of age. The relative risks of malnutrition were interpreted as being directly proportional to the incidence of underweight. Again, the model output was used to generate mid-range estimates; the high relative risks were calculated as a doubling of the mid-range estimate.

Malaria

Estimates for the projected populations at risk of *Plasmodium falciparum* malaria were based on the MARA/ARMA model (MARA/ARMA 1998). As for other health outcomes, the model output was used to generate mid-range estimates; the high relative risks were calculated as a doubling of the mid-range estimate.

The total estimated excess numbers of cases are shown in Tables 1-3 in Annex 3.

Summary

The projected relative risks attributable to climate change in 2030 vary by health outcome and region, and are largely negative, with the majority of the projected disease burden due to increases in diarrheal disease and malnutrition, primarily in low-income populations already experiencing a large burden of disease (McMichael et al. 2004). Absolute disease burdens depend on assumptions of demographic change, future baseline disease incidence, and the extent of adaptation. Table 3 summarizes the current number of cases of the three health outcomes, the projected number of cases under the unmitigated emissions scenario, and the percentage increase (Ebi 2008).

Table 3: Comparison of current diarrheal disease, malnutrition, and malaria cases with estimated climate change impacts in 2030 assuming the 750 ppm of CO_2 scenario (thousands of cases)

	Diarrheal diseases	Malnutrition	Malaria

Total	4,513,981	46,352	408,227
Climate change impacts	131,980	4,673	21,787
% increase	3%	10%	5%

Climate change alone, without considering other factors that could increase or decrease incidence, is projected to increase the burden of diarrheal diseases, malnutrition, and malaria by several percentage points worldwide. Although there is high uncertainty in the regional estimates, as would be expected, those regions with high current burdens of these health outcomes are projected to experience the largest increase in 2030. For example, unmitigated emissions are projected to more than double the number of incident cases of diarrheal disease in Africa and parts of Southeast Asia. The largest increase in malnutrition is projected to occur in the parts of Southeast Asia where malnutrition is currently severe. The largest increase in incident cases of malaria is projected to occur in Africa and parts of the Eastern Mediterranean region.

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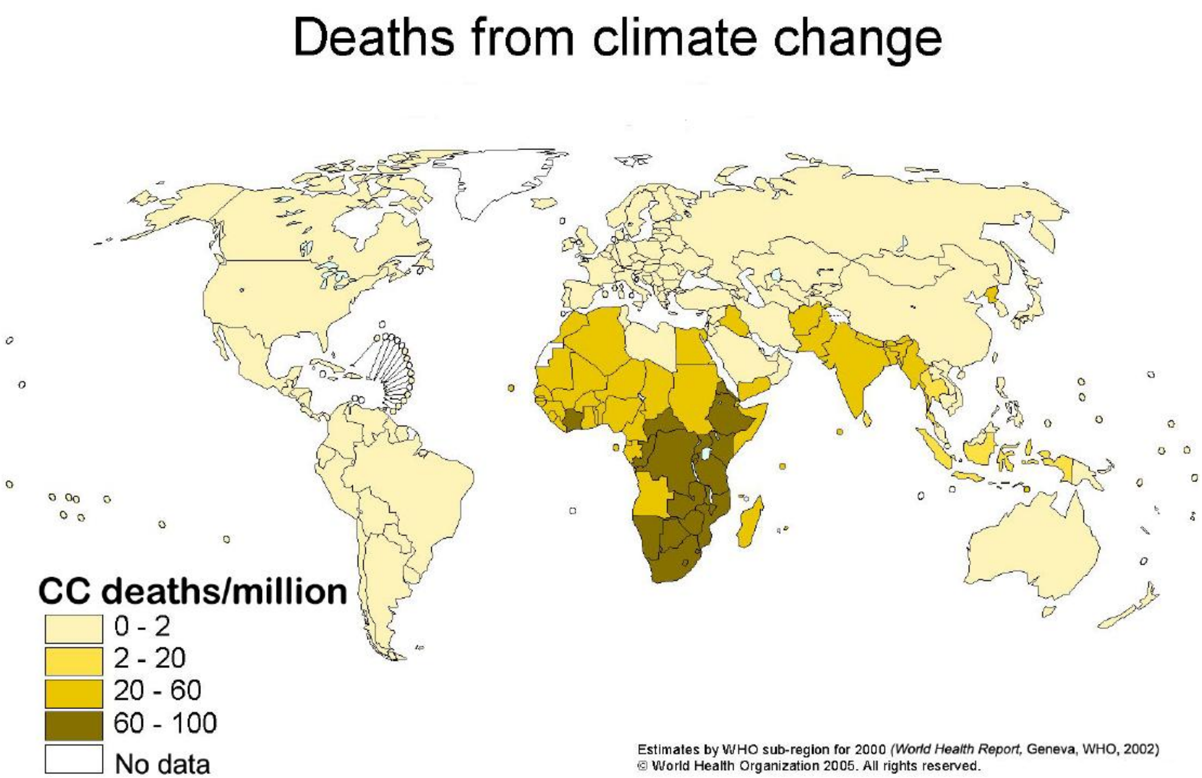
Climate-Associated Changes in Health Outcomes

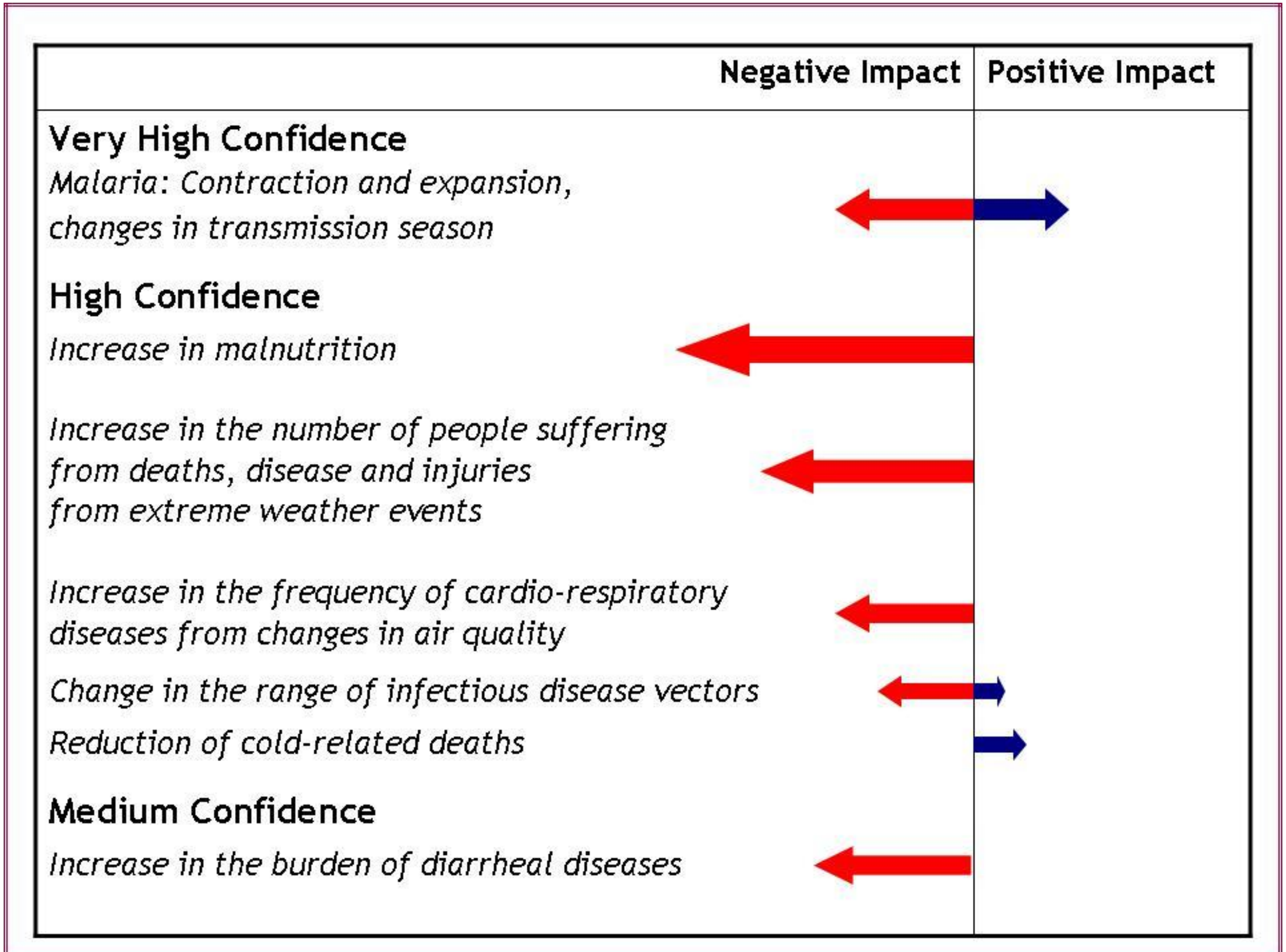
Kristie L. Ebi, Ph.D., MPH
Carnegie Institution for Science
27 January 2011

IPCC AR4 Health Impacts of Climate Change

- Emerging evidence of climate change impacts:
  - Altered distribution of some vectors
  - Altered seasonal distribution of some pollen species
  - Increased risk of heatwave deaths

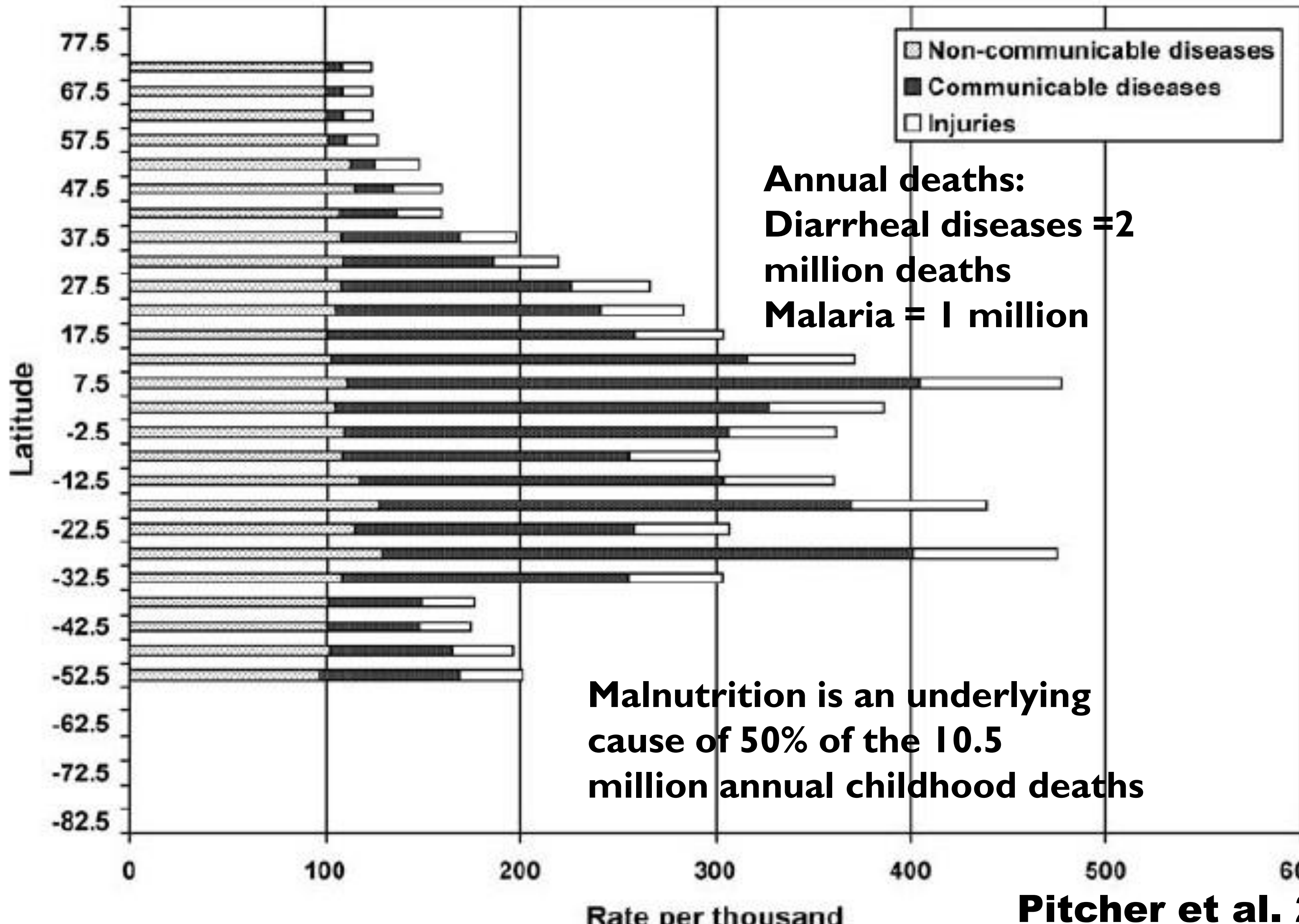


Direction and Magnitude of Climate Change Health Impacts



IPCC 2007

Sum of Years of Life Lost and Years of Life Lived with Disability

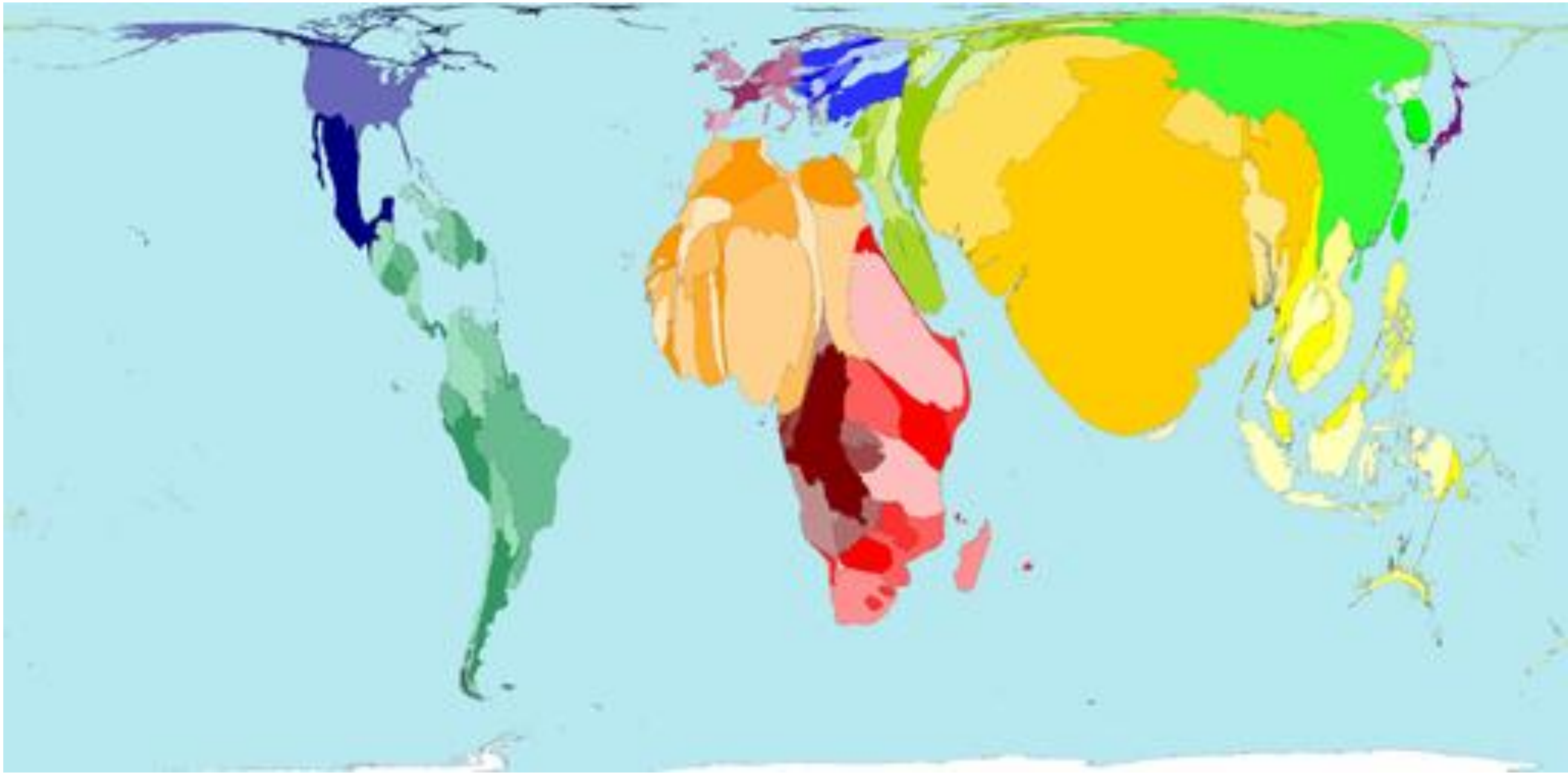


Annual deaths:
Diarrheal diseases =2 million deaths
Malaria = 1 million

Malnutrition is an underlying cause of 50% of the 10.5 million annual childhood deaths

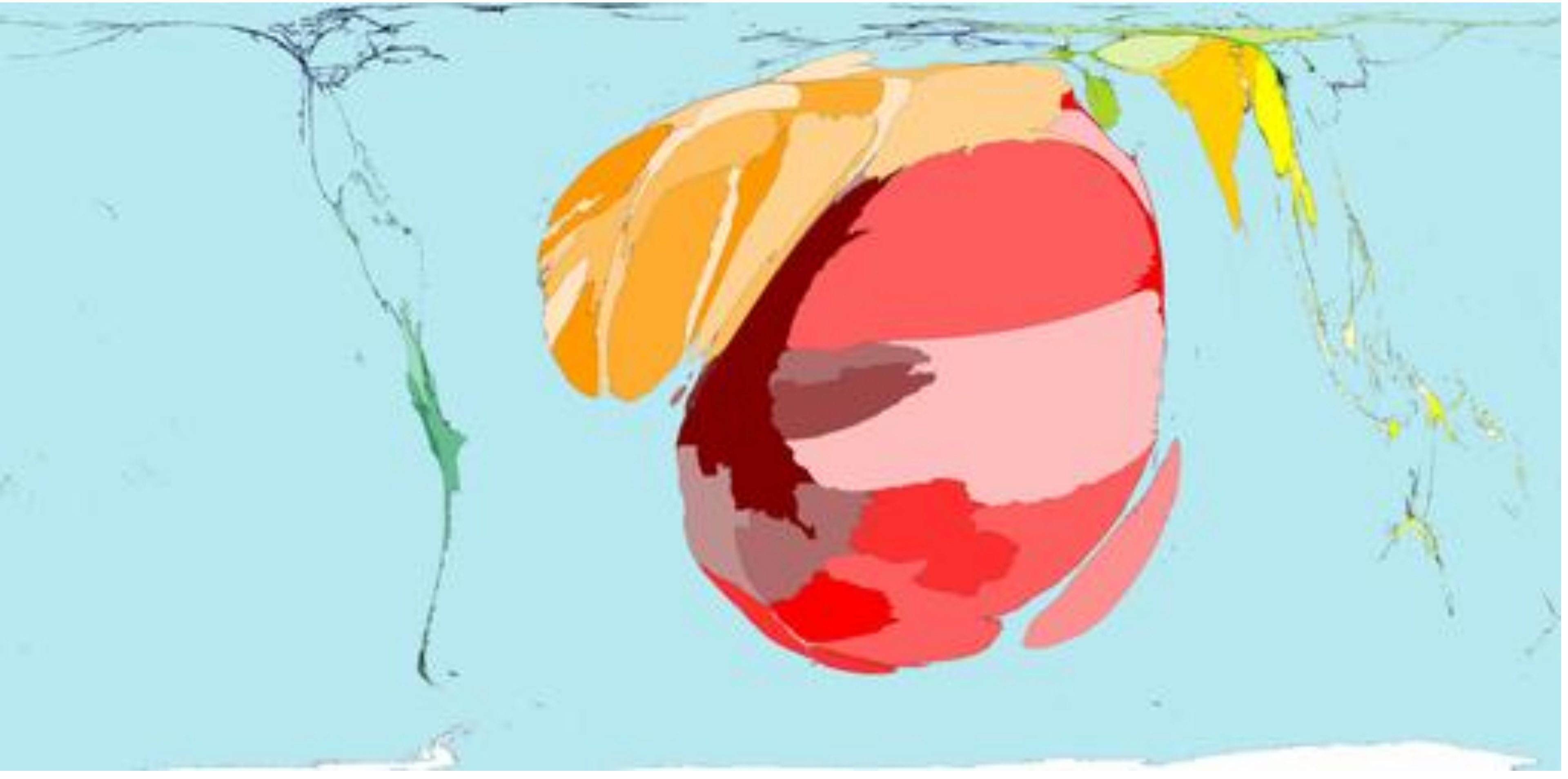
Pitcher et al. 2008

Prevalence Childhood Diarrhea



www. Worldmapper.org

Malaria Cases



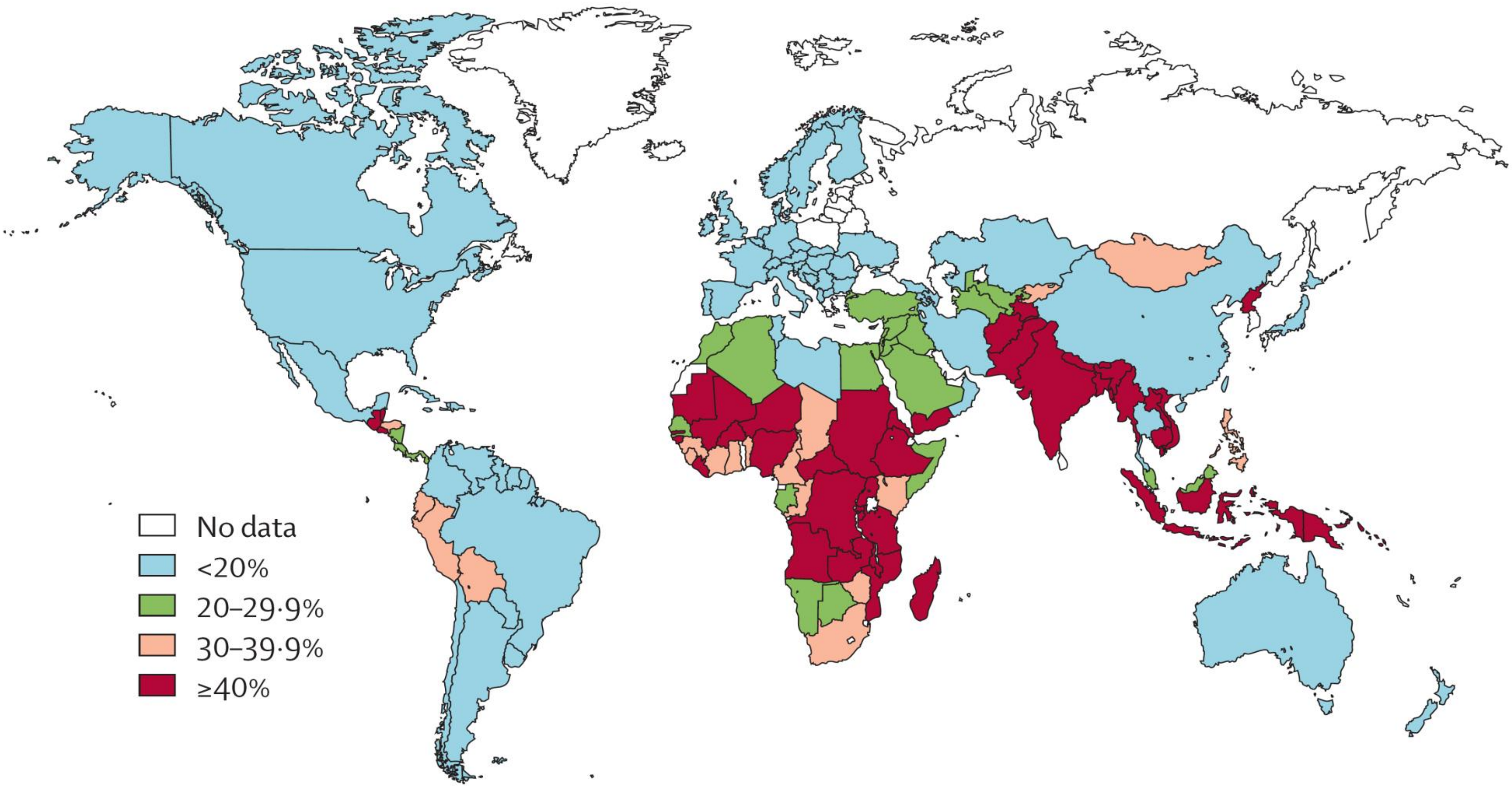
www. Worldmapper.org

Global Burden of Disease Undernutrition

- 21% disability-adjusted life-years (DALYs) for children younger than 5 years
- 35% child deaths - 11% of total global Burden of Disease
- When all the effects of malnutrition are considered (including loss of cognitive function, poor school performance, and loss of future earning potential), the total estimated costs of environmental risk factors could be as high as 8-9% of a typical developing country's GDP in South Asia or Sub-Saharan Africa

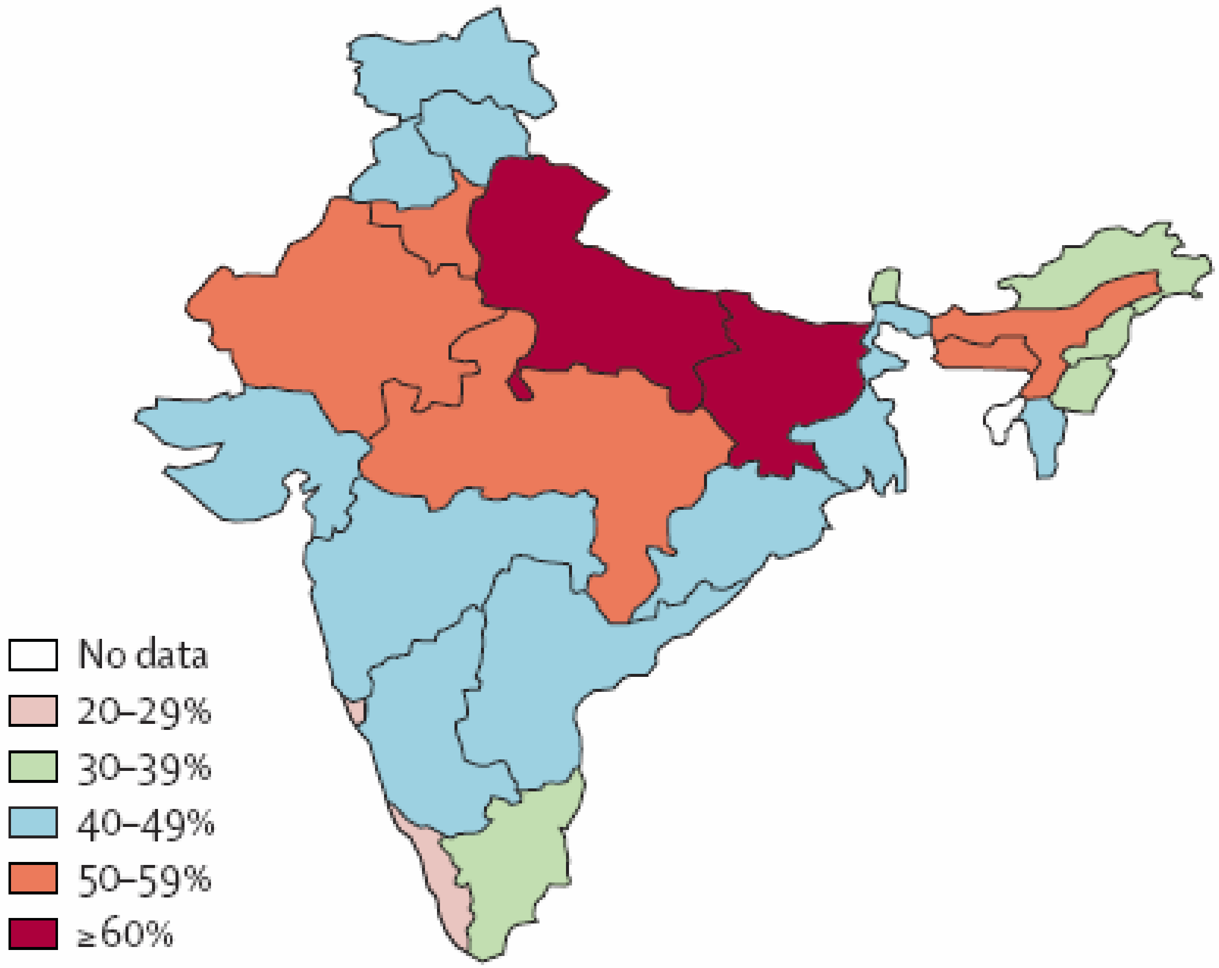
Black et al. 2008

Prevalence of Stunting in Children Under 5 years (2005)



Black et al. 2008

Prevalence of Stunting in Children Under 5 years in India (2005)



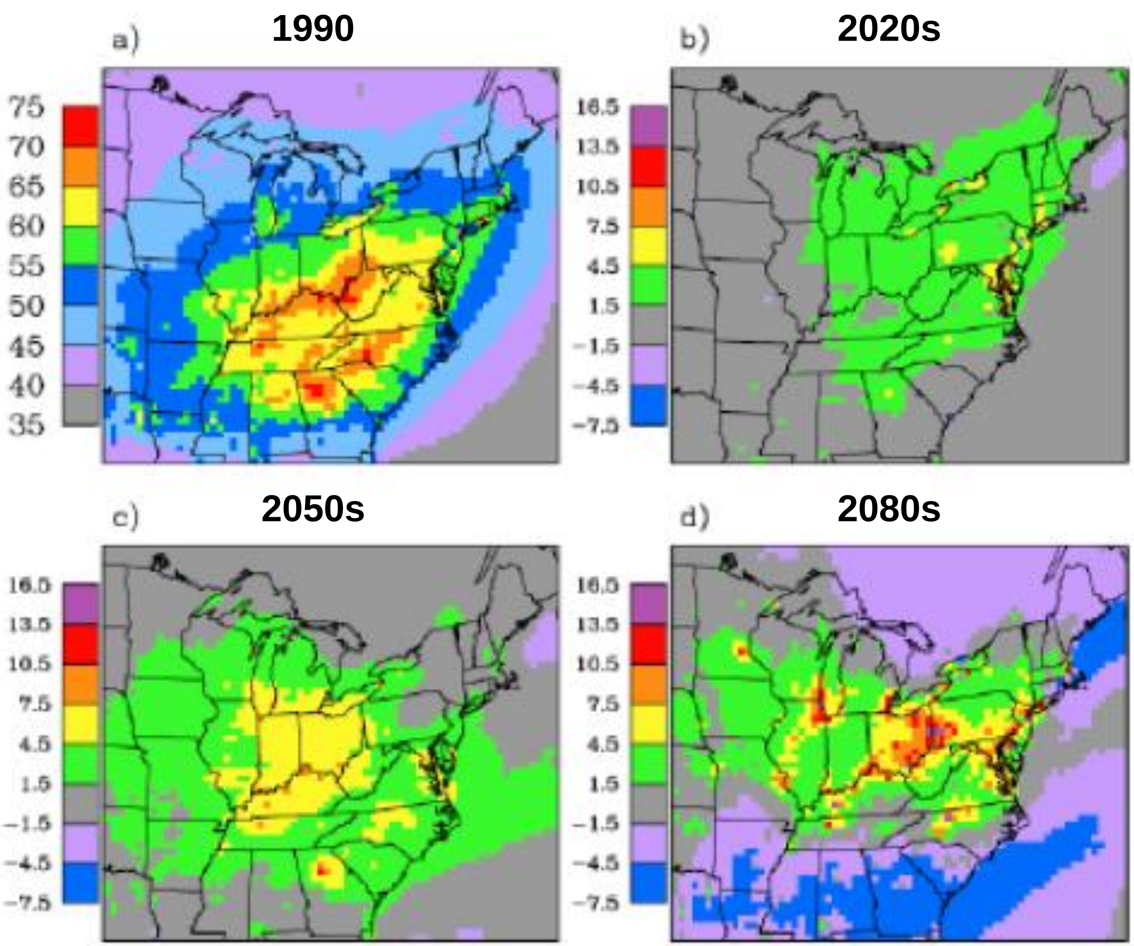
India has more than 61 million stunted children, 51% of the national population and 34% of the global total. However, stunting prevalence varies substantially by state.

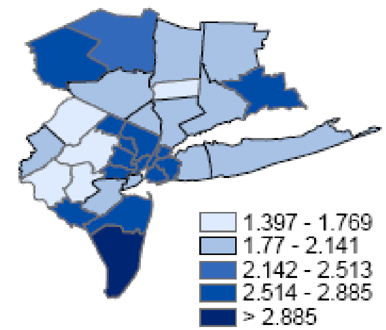
Black et al. 2008

Interactions of Infectious Diseases and Undernutrition

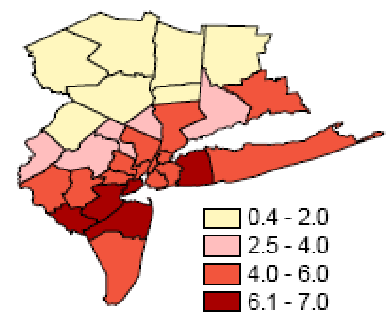
- Poor nutritional status, especially in infants and young children, makes infections more severe and prolonged, and often more frequent
  - In low-income countries, 27% of children under the age of 5 are chronically undernourished or stunted, and 23% are underweight
- Almost all infections influence a child's nutritional status through loss of appetite, changes in intestinal absorption, metabolism, and excretion of specific nutrients
  - The effects of infections appear to be directly proportional to the severity of the infection

Projected Changes in Ozone and Related Deaths, New York Metro Area





Baseline Daily Mortality Rate per 100,000



Percent Increase in O_3-related Deaths

2050s

Kinney et al. 2006

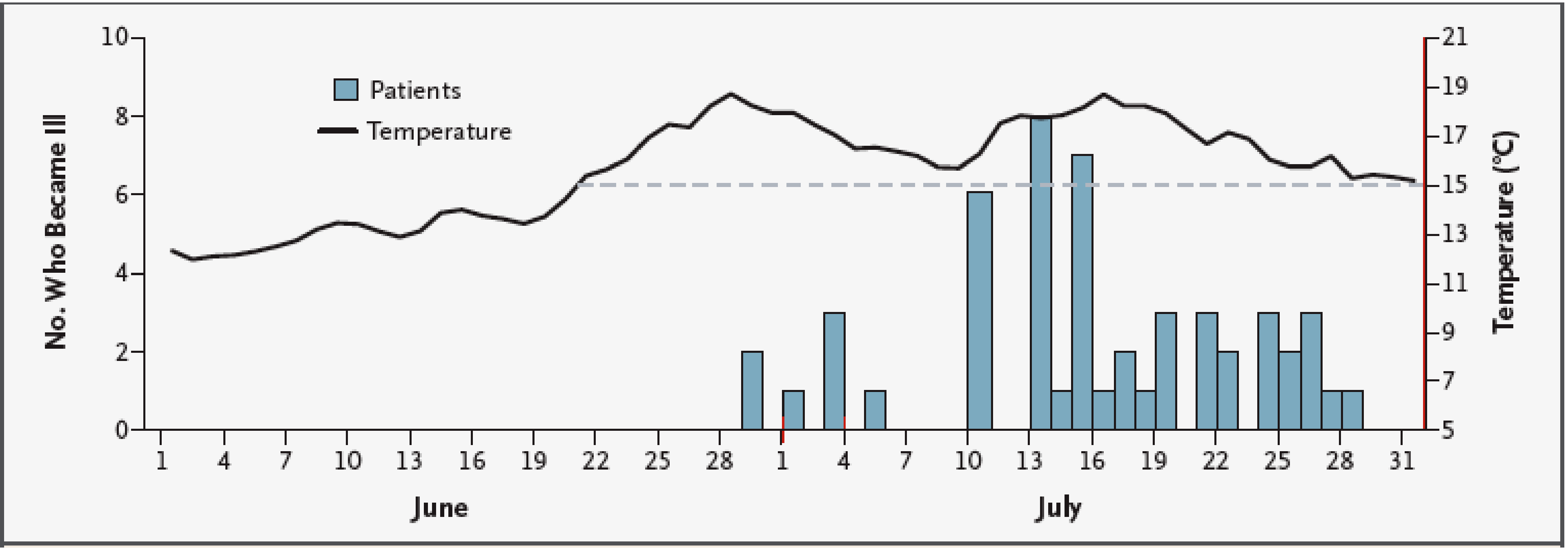
Climate Change Impacts in 2030 under 750 ppm CO_2 Scenario (thousands of cases)

Estimated costs to treat the climate change-related cases = $3,992 to $12,603 million

	Diarrhea	Malnutrition	Malaria
Total	4,513,981	46,352	408,227
Climate change impacts	131,980	4,673	21,787
% increase	3%	10%	5%

Ebi 2008

Vibrio parahaemolyticus Infections by Harvest Date and Mean Daily Water Temperature



McLaughlin et al. 2005

Research Needs

- Improve characterization of exposure- response relationships, particularly at regional and local levels, including identifying thresholds and particularly vulnerable groups
- Collect data on the early effects of changing weather patterns on climate-sensitive health outcomes
- Collect and enhance long-term surveillance data on health issues of potential concern, including vectorborne and zoonotic diseases, air quality, pollen and mold counts, reporting of food- and water-borne diseases, morbidity due to temperature extremes, and mental health impacts from extreme weather events
- Develop quantitative models of possible health impacts of climate change that can be used to explore the consequences of a range of socioeconomic and climate scenarios
- Understand local- and regional-scale vulnerability and adaptive capacity to characterize the potential risks and the time horizon over which risks might arise
- Develop downscaled climate projections at the local and regional scale in order to conduct the types of vulnerability and adaptation assessments that will enable adequate response to climate change, and to determine the potential for interactions between climate and other risk factors, including societal, environmental, and economic
- Improve understanding of the design, implementation, and monitoring of adaptation options
- Understand the co-benefits of mitigation and adaptation strategies
- Enhance risk communication and public health education

Estimating the Economic Value of Health Impacts of Climate Change

Maureen L. Cropper
University of Maryland and Resources for the Future

How should we value the health impacts of climate change? The answer is, in principle, simple: we should value them by what people are willing to pay to avoid them. This includes the costs of averting behavior—the costs of the energy used to mitigate the effects of temperature extremes on health—as well as the cost of the illnesses themselves. Obtaining empirical estimates of WTP for health—for adults and children—in countries at all income levels is challenging. The purpose of this presentation is to discuss in more detail what empirical estimates are needed and how they might be obtained, in the short run, through benefits transfer.

Nature of Health Impacts to Be Valued

The number of deaths and illnesses associated with climate change are likely to be greatest in developing countries, at least over the rest of this century. Mc Michaels et al. (2004) estimate that in 2000, climate change was associated worldwide with 166,000 deaths—77,000 due to malnutrition, 47,000 associated with diarrhea, and 27,000 with malaria (see Figure 1). The highest number of deaths (per 100,000 persons) was predicted to occur in Africa, South Asia and the Middle East. It should also be noted that the majority of these deaths are children, and that deaths among children account for the bulk of the 5.5 million Disability-Adjusted Life Years (DALYs) that Mc Michael et al. (2004) estimate were lost due to climate change in 2000.

This implies that we must value the lives of children (and adults) in developing countries. The illnesses that these individuals suffer are also important and must be valued. These include non-fatal cases of diarrhea and malaria, respiratory illnesses and cardiovascular disease. Adults and children in higher income countries will also be affected by climate change. The same valuation concepts should be applied in all cases, as discussed in the next section.

Valuating Mortality

To value risk of death among adults, the appropriate valuation concept is what adults would pay to reduce their own risk of dying. For children, it is what parents would pay to reduce their children's risk of dying. Willingness to pay is constrained by ability to pay, and should increase with income, assuming life extension is a normal good. This implies that WTP will generally be lower in low-income than in high-income countries. It is often suggested that lives should be valued equally in all countries—that the same WTP amount should be used regardless of income. The problem with this suggestion is that it forces people in developing countries to spend more on risk reduction than they would choose, based on their own preferences. The correct valuation concept is what a person would pay for a small reduction in his risk of death.

By convention, the sum of WTPs for small risk changes is expressed as the Value per Statistical Life (VSL)—the sum of WTPs for risk reductions that sum to one statistical life saved. For example, if each of 10,000 people would pay $100 to reduce their risk of dying over the coming year, the VSL would be $1,000,000 (10,000*$100). The risk reduction (1 in 10,000) summed over 10,000 people would result in one statistical life saved.

Empirical estimates of the VSL for adults most frequently come from hedonic wage studies, which estimate compensating wage differentials in the labor market, or from contingent valuation (stated preference) surveys in which people are asked directly what they would pay for a reduction in their risk of dying. The empirical literature on the VSL in high income countries is large.[1] There are approximately 4 dozen compensating wage studies in high income countries (see, for example, Viscusi and Aldy (2003)) and over 4 dozen stated preference studies (Braathen et al., 2009). Several recent meta-analyses have summarized the results of these studies (Cropper, Hammitt and Robinson, 2011). The literature in middle income countries is much smaller.[2] Robinson and Hammitt (2009) review 8 wage-risk and 9 stated-preference studies conducted in 9 middle-income countries. Braathen et al. (2009) cite14 stated preference studies conducted in middle-income countries, but only one in a low income country (Bangladesh).

VSL Benefits Transfer

What is clear is that the developing country literature at this point is not sufficiently mature to provide estimates of the VSL for individual countries. This suggests transferring estimates from countries where better studies exist to countries for which there are no empirical estimates of the VSL. Most transfers are based on income differences between countries. The most common approach to benefits transfer assumes that the ratio of the VSL to per capita income is constant among countries. (This is equivalent to assuming an income elasticity of the VSL = 1.) Transferring values from the US, where this ratio is approximately 140 to 1, implies that the ratio of the VSL to income is 140 to 1 for all countries.

Recent analyses, however, suggest that an income elasticity of 1 may be inappropriate for low-income countries. This based partly on a comparison of the ratio of the VSL to income in high income countries with the corresponding ratio based on studies in middle income countries. Preliminary analyses (Cropper and Sahin, 2009) suggest the ratio is closer to 80 to 1 for middle income countries v. 140 to 1 for high income countries. This suggests that the income elasticity of the VSL is > 1. Analyses of the income elasticity of the VSL in the US (Costa and Kahn, 2004; Kniesner et al. 2011) and Taiwan (Hammitt, Liu and Liu, 2000) also suggest that the income elasticity of the VSL is larger at low incomes than at high incomes. Pending additional studies, Hammitt and Robinson (2010) suggest using an income elasticity of the VSL of 1.5 in addition to an income elasticity of 1.0 to provide a range of values of for the VSL in middle and low income countries.

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[1] Cropper, Hammitt and Robinson (2011) summarize this literature, including recent meta-analyses.

[2] I follow the World Bank's definition, based on market exchange rates. The groups are: low income, $995 or less; lower middle income, $996 - $3,945; upper middle income, $3,946 - $12,195; and high income, $12,196 or more.

Estimating the VSL for Children

There is a small but growing literature on parents' WTP to reduce health risks to their children, including mortality risks. In the US and Europe, revealed preference studies have used information on the purchase of car seats and bicycle helmets to infer WTP for reduced death and injury. Other studies are based on parents' WTP for chelation therapy for children with body lead burdens. Some of the literature relies on stated preference studies. As stated in a recent OECD volume on children's health (OECD, 2010) only 15 studies directly compare parents' willingness to pay for improvements in their own health with WTP for improvements in their children's health. Many of these studies value reductions in acute illness, and only one study was conducted outside of the US and Europe (Liu et al., 2000).

The consensus from studies conducted in high income countries is that parents are willing to pay more to reduce health risks to young children than to themselves—generally about twice as much—but that this effect decreases with child age. The result is also not universal: Jenkins et al. (2001) and Mount et al. (2001) find that parents are willing to pay more to reduce mortality risks to themselves than to their children. The USEPA uses the same VSL for children as for adults.

The question is whether the VSL is higher for children than for adults in low income countries; in particular, in countries with substantial under-5 child mortality and high fertility rates. There no studies of which I know that directly address this issue. In studies conducted for the World Bank (Larsen, 2011), VSLs used for children are often less than those used for adults. This is a topic clearly requiring more research. The literature on the allocation of food and health care resources within the household may shed some light on this issue.

Valuing Morbidity

Willingness to pay for avoided illness should capture the value of the pain and suffering avoided, as well as the value of time lost due to illness (both leisure and work time) and the costs of medical treatment. If some of these costs are not borne by the individual, and are therefore not reflected in his willingness to pay, the value of the avoided costs must be added to WTP to measure the total benefits of reduced illness. The Cost of Illness (COI) approach, which captures medical costs and lost productivity, is often used as a lower bound to the more comprehensive valuation concept.

In high income countries, WTP estimates for avoided morbidity are available for some illnesses, but COI estimates are often used to measure the value of avoided illness. Due to the heterogeneous nature of illness, providing WTP (or even COI) estimates for a variety of diseases is a huge task. The most sensible approach would be to determine the diseases that are likely to lead to the largest number of DALYs lost due to illness and to focus on obtaining COI estimates for these diseases.

Morbidity, especially in Sub-Saharan Africa, is likely to have impacts on the economy beyond traditional illness costs. Child morbidityis likely to affect human capital formation. (See for example, Alderman, Hoddinott and Kinsey(2006) on the impacts of malnutrition on human capital formation.) Malaria may have impacts on economic growth through land use, crop choice and other mechanisms (Gallup and Sachs, 2001; Tol, 2008). These effects are certainly worth exploring.

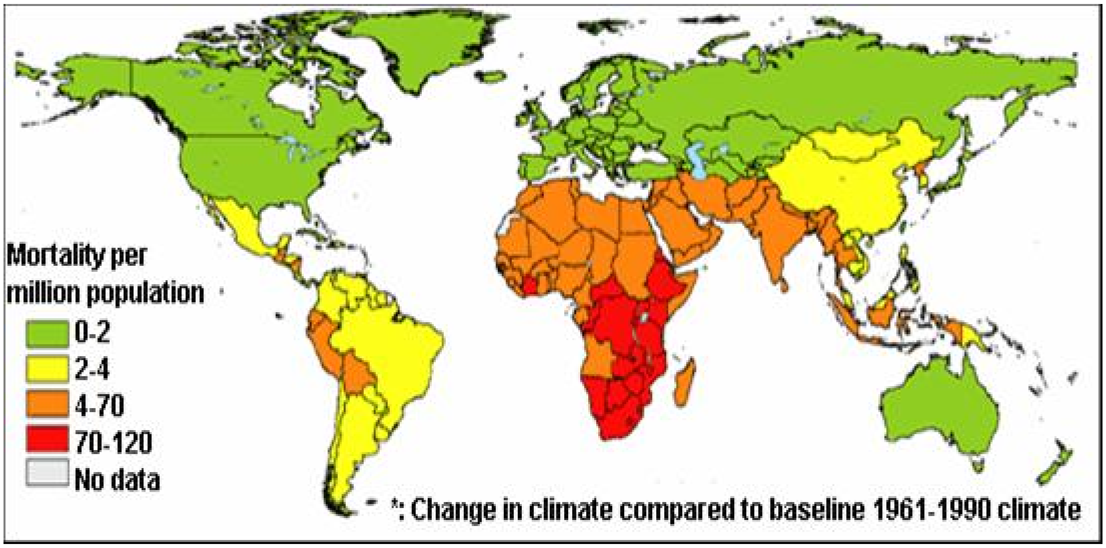

Figure 1: Estimated Deaths due to Climate Change in 2000, by WHO Sub-Region

Source: Map created by Center for Sustainability and the Global Environment (SAGE), University of Wisconsin using data from McMichael et al. (2004).

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Estimating the Economic Value of Health Impacts of Climate Change

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January 27th, 2011

The Task

- Given estimates of health impacts of climate change by region and time period, monetize value of health damages
- Should value damages after adaptation, plus costs of adaptation; presentation will focus on valuing health impacts per se
- Value changes in mortality risks
  - For children and adults
  - As a function of per capita income
- Value changes in morbidity

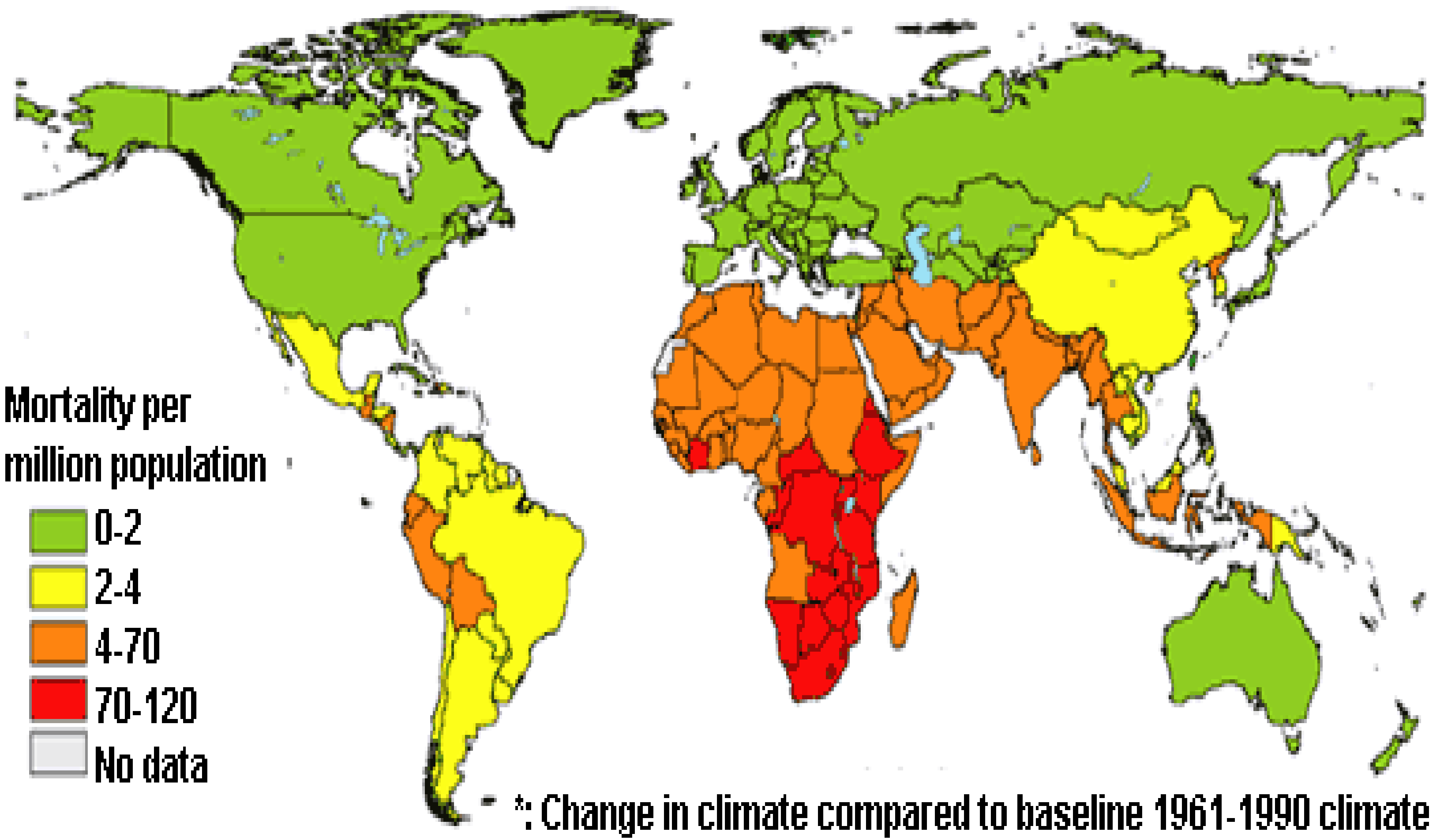
Presentation

- Main health impacts to be valued and countries in which they are likely to occur
- Valuation concepts
- Estimating the value of mortality risk reductions for adults in low income countries
- Estimating the value of mortality risk reductions for children in low income countries
- Valuing morbidity

Which Health Effects to Value?

- Possible health endpoints include:
  - Malnutrition
  - Diarrheal disease
  - Vector-borne diseases (malaria, dengue fever)
  - Deaths associated with temperature extremes, air pollution
  - Deaths associated with climate-related disasters
- According to McMichael et al. (2004) most DALYs lost due to:
  - Malnutrition
  - Diarrhea
  - Vector-borne disease

Estimated Deaths due to Climate Change* in 2000, by WHO subregion



Source: Map created by SAGE using data from McMichael et al. (2004

Overview of Approaches to Valuing Death and Injury

- Human Capital - Cost of Illness (COI)
  - Values a life by the PDV of forgone earnings
  - Values an injury by medical costs and lost productivity
- Value of Statistical Life - Willingness to Pay
  - Values a life by sum of what people will pay for reductions in risk of death
  - For injuries, adds WTP for pain and discomfort to COI
- VSL – WTP approach is theoretically correct

Valuing Reductions in Risk of Death

- Goal is to estimate what an individual is willing and *able* to pay for a ***small reduction*** in his risk of death
  - It does <u>NOT</u> measure the amount an individual would pay to avoid death with certainty
- Suppose a person is willing to pay $500 to reduce his risk of dying by 1 in 10,000 over the coming year:
  - If 10,000 people will each pay $500 for a 1 in 10,000 risk reduction, together they will pay $5,000,000 for risk reductions that sum to 1 statistical life saved
  - We say that $5,000,000 is the ***Value of a Statistical Life***.

Approaches to Valuing Mortality Risk Reductions

- Revealed Preference Studies
  - Use compensating wage (CW) differentials to value risk of death (most common approach)
  - Use data on purchase of safer vehicles or safety equipment (e.g., bicycle helmets)

- Stated Preference Studies
  - Ask people directly what they would pay for a change in risk of death (e.g., Contingent valuation (CV) studies)

Overview of VSL Estimates in the Literature

High-income OECD countries

- Approximately 4 dozen CW studies (30 in USA)
- Over 4 dozen CV studies
- 6 published meta-analyses of these studies since 2000

Middle-income countries

- Fewer than a dozen CW studies
- About two dozen stated preference studies

Low-income countries

- 1 study for Bangladesh; none for Africa

How Is VSL Transferred from One Country to Another?

- Most common approach is:

$$VSL_{India} = VSL_{USA} * (Y_{India} / Y_{USA})^{\varepsilon}$$

where ε is the income elasticity of the VSL. Usual assumption is that ε = 1.

- This implies:

$$VSL_{USA} / Y_{USA} = VSL_{India} / Y_{India}$$

Is the Conventional Approach Correct?

- <u>In High Income Countries VSL/Y ratio ≈ 140</u>
  - Ratio of VSL/Y is about 140 in Miller (2000) based on studies in 13 high income countries
- <u>In Middle Income Countries VSL/Y ratio ≈ 80</u>
  - Review of 17 VSL studies in middle income developing countries by Robinson and Hammitt (2009) implies a ratio of 80 (using better studies)
- This suggests that $\varepsilon > 1$.
- US labor market studies suggest that ε increases as incomes fall

How to Estimate the VSL for Developing Countries?

- Hammitt and Robinson (2010) suggest using an income elasticity of 1.5
  - Supported by studies by Costa and Kahn (2004) and Hammit, Liu and Liu (2000)
- Cropper and Sahin (2009) also suggest ε = 1.5 based on a life-cycle consumption model
- Using a US VSL of $6.3 million (2007 USD) and Y_{US} = $46,000 implies:
  - $VSL_{India} = (Y_{India})^{1.5} * (.64)$

How to Estimate the VSL for Children?

- Studies of parents' willingness to pay to reduce risks to children used to estimate the VSL
- Studies in high income countries suggest child VSL ≈ 2 x adult VSL
- However . . . .
  - Parents' WTP may be different in countries where 1 out of 5 children die before age 5
  - USEPA uses same value for adults and children
  - Many World Bank studies have used Human Capital approach for children

Valuing Morbidity

<u>Want to capture:</u>

- Value of lost productivity
- Cost of medical treatment
- Value of discomfort, inconvenience and pain

Cost of Illness (COI) = Value of lost work time + Cost of medical treatment

Could add value of Quality-Adjusted Life Years (QALYs) lost to COI to capture pain and suffering since few direct WTP estimate available

Valuing Morbidity

- In US studies of health effects of air pollution, value of avoided morbidity is small relative to premature mortality
  - Case of chronic bronchitis ≈ .05 VSL
- Back-of-the-envelope calculations should be done before refining estimates
- Other impacts that may be relevant are:
  - Macroeconomic impacts of malaria (Gallup and Sachs, 2001; Tol, 2008)
  - Impacts of malnutrition on human capital formation (Alderman, Hoddinott and Kinsey, 2003)

Conclusions

- Greatest disease burden from climate change likely to be in Sub-Saharan Africa, South Asia and the Middle East
- Much of the disease burden will fall on children
- Value associated with health impacts depends crucially on:
  - How value of morality risks varies with income
  - How risks to children are valued v. risks to adults
- Most of the disease burden likely to come from mortality
  - But, link between diseases and economic growth could be important

Sea Level Impacts of Climate Change

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INTRODUCTION

Sea-level rise has been seen as a major threat to low-lying coastal areas around the globe since the issue of human-induced global warming emerged in the 1980s. What is often less appreciated is that more than 200 million people are already vulnerable to flooding by extreme sea levels around the globe. This population could grow fourfold to the 2080s just due to rising population/coastward migration. These people generally depend on natural and/or artificial flood defences and drainage to manage the risks, with the most developed and extensive artificial systems in Europe (especially around the southern North Sea) and East Asia. Most threatened are the significant populations (at least 20 million people today) already living below normal high tides in many countries such as the Netherlands and the USA. Hurricane Katrina's impacts on New Orleans in 2005 remind us of what happens if such defences fail. Increasing mean sea level and more intense storms will exacerbate these risks. Despite these threats, the actual consequences of sea-level rise remain uncertain and contested. This reflects far more than the uncertainty in the magnitude of sea-level rise and climate change, with the uncertainties about our ability to adapt to these challenges being a major uncertainty (Nicholls and Tol, 2006; Nicholls et al., 2007a).

CLIMATE CHANGE AND GLOBAL/RELATIVE SEA-LEVEL RISE

Human-induced climate change is expected to cause a profound series of changes including rising sea level, higher sea-surface temperatures, and changing storm, wave and run-off characteristics. Although higher sea level only directly impact coastal areas, these are the most densely-populated and economically active land areas on Earth, and they also support important and productive ecosystems that are sensitive to sea level and other change. Rising global sea level due to thermal expansion and the melting of land-based ice is already being observed and this rise is likely to accelerate through the 21st century. From 1990 to the last decade of the 21st century, a total rise in the range 18–59 cm has been forecast by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Meehl et al, 2007). It is worth noting that the current satellite observations of global sea-level rise are at the high end of the predicted SRES scenarios (Rahmstorf et al., 2007), and if recent ice sheet discharge continues through the 21st Century at current rates, the maximum projected rise increases to 79 cm[1]. Even this scenario excludes uncertainties due to collapse of the large ice sheets, and as noted in the IPCC Synthesis Report (2007), the quantitative AR4 scenarios do ***not*** provide an upper bound on sea-level rise during the 21st Century. A global rise of sea

[1] Allowing for ice-melt uncertainties

level exceeding one metre remains a low probability, but physically-plausible scenario for the 21st Century due to large uncertainties concerning ice sheet dynamics and their response to global warming. While these high end scenarios may be relatively unlikely, their large potential impacts makes them highly significant in terms of climate risk. There is also increasing concern about higher extreme sea levels due to more intense storms superimposed on these mean rises, especially for areas affected by tropical storms. This would exacerbate the impacts of global-mean sea-level rise, particularly the risk of more damaging floods and storms.

When analysing sea-level rise impacts and responses, it is (Nicholls, 2010) fundamental that impacts are a product of ***relative*** (or local) sea-level rise rather than global changes alone. Relative sea-level change takes into account the sum of global, regional and local components of sea-level change: the underlying drivers of these components are (1) climate change such as melting of land-based ice, thermal expansion of ocean waters, and changing ocean dynamics, and (2) non-climate uplift/subsidence processes such as tectonics, glacial isostatic adjustment, and natural and human-induced subsidence. Hence relative sea-level rise is only partly a response to climate change and varies from place to place. Relative sea level is presently falling due to ongoing glacial isostatic adjustment (rebound) in some high-latitude locations that were formerly sites of large (kilometre-thick) glaciers, such as the northern Baltic and Hudson Bay, while RSLR is more rapid than global-mean trends on subsiding coasts, including many populous deltas. Most dramatically, human-induced subsidence of susceptible areas due to drainage and withdrawal of groundwater can produce dramatic RSLR, especially cities built on deltaic deposits. Over the 20th century, parts of Tokyo and Osaka subsided up to 5 m and 3 m, respectively, a large part of Shanghai subsided up to 3 m, and most of Bangkok subsided up to 2 m[2]. Such human-induced subsidence can be managed by stopping shallow sub-surface fluid withdrawals, but natural "background" rates of subsidence will continue. The four example cities have all seen a combination of such policies combined with the provision of flood defences and pumped drainage to avoid submergence and/or frequent flooding. In contrast, Jakarta and Metro Manila are subsiding cities where little systematic action to manage and reduce the subsidence are in place as yet.

SEA-LEVEL RISE AND RESULTING IMPACTS

Relative sea-level rise has a wide range of effects on the natural system, with the five main effects being summarized in Table 1. Flooding/submergence, ecosystem change and erosion have received significantly more attention than salinisation and rising water tables. Along with rising sea level, there are changes to all the processes that operate around the coast. The immediate effect is submergence and increased flooding of coastal land, as well as saltwater intrusion into surface waters. Longer term effects also occur as the coast adjusts to the new environmental conditions, including wetland loss and change in response to higher water tables and increasing salinity, erosion of beaches and soft cliffs, and saltwater intrusion into groundwater.

[2] The maximum subsidence is reported as data on average subsidence is not available.

These lagged changes interact with the immediate effects of sea-level rise and generally exacerbate them. For instance, coastal erosion will tend to degrade or remove natural protective features (e.g. saltmarshes, mangroves and sand dunes) so increasing the impact of extreme water levels and hence the risk of coastal flooding.

A mean rise in sea level also raises extreme water levels, as shown by Zhang et al (2000) on the US East Coast, and this is widely applied in impact studies for future conditions. Changes in storm characteristics could also influence extreme water levels both positively and negatively. For example, the widely debated increase in the intensity of tropical cyclones would increase in general terms extreme water levels in the areas affected.

Changes in natural systems as a result of sea-level rise have many important direct socio-economic impacts on a range of sectors with the effect being overwhelmingly negative. For instance, flooding can damage the extensive coastal infrastructure, ports and industry, the built environment, and agricultural areas, and in the worst case lead to significant mortality (e.g., Cyclone Nargis (2008), Myanamar). Erosion can lead to losses of the built environment and related infrastructure and have adverse consequences for sectors such as tourism and recreation. In addition to these direct impacts, there are indirect impacts such as adverse effects on human health: for example, mental health problems increase after a flood, or the release of toxins from eroded land fills and waste sites which are commonly located in low-lying coastal areas, especially around major cities. Economically, sea-level rise will also have direct and indirect effects (see Tol, 2011, these abstracts). Thus, sea-level rise has the potential to trigger a cascade of direct and indirect human impacts.

RECENT IMPACTS OF SEA-LEVEL RISE

Over the 20th century global sea level rose about 18 cm. While this change may seem small, it will have had many significant effects, most particularly in terms of the return periods of extreme water levels (e.g., Zhang et al., 2000; Menéndez and Woodworth, 2010), and promoting a widespread erosive tendency for coasts. However, linking sea-level rise quantitatively to impacts is quite difficult as the coastal zone has been subjected to multiple drivers of change over the 20th Century (Rosenzweig et al., 2007). Good data on rising sea levels has only been measured in a few locations, and defences and other coastal infrastructure have often been upgraded substantially through the 20th Century, especially in those (wealthy) places where there are sea-level measurements. Most of this defence upgrade reflects expanding populations and wealth in the coastal flood plain and changing attitudes to risk, and relative sea-level rise may not have even been considered in the design. Equally, erosion can be promoted by processes other than sea-level rise (Table 1), and human reduction in sediment supply to the coast must contribute to the observed changes. Decline in intertidal habitats such as saltmarshes, mudflats and mangroves is often linked to sea-level rise, but these systems are also subject to multiple drivers of change, including direct destruction (Nicholls, 2004). Hence, while global sea-level rise is a pervasive process, it is difficult to unambiguously link it to impacts, except in some special cases – most recent coastal change was a response to multiple drivers of change.

On the US east coast, relative sea levels have risen at variable rates between 2 and 4 mm/yr over the 20th century, reflecting a combination of global rise and subsidence. Both sea level and coastal change has been measured during the 20th century, providing a laboratory for exploring shoreline response to sea-level rise. Comparing the rate of shoreline retreat and the long-term rate of relative sea-level rise away from inlets and engineered shores, supports the concept of the 'Bruun Rule' where the shoreline retreat rate is 50 to 100 times the rate of sea-level rise (Zhang et al., 2004), although this relationship remains controversial. Near inlets, the indirect effects of sea-level rise which cause the associated estuary/lagoon to trap beach-sized sediment can have much larger erosional effects on the neighbouring open coasts than predicted by the Bruun Rule (Stive, 2004). Hence, more general relationships are required to understand coastal change taking account of sea-level change, sediment supply and coastal physiography. Human responses to sea-level rise are even more difficult to document. Human abandonment of low-lying islands in Chesapeake Bay, USA during the late 19th/early 20th century does seem to have been triggered by a small acceleration of sea-level rise and the resulting land loss (Gibbons and Nicholls, 2006).

There have certainly been impacts from the relative sea-level rise resulting from large rates of subsidence, such as the Mississippi delta where relative sea-level rise is 5 to 10 mm/yr. Between 1978 and 2000, 1565 km^2 of intertidal coastal marshes and adjacent lands were converted to open water, due to sediment starvation and increases in the salinity and water levels of coastal marshes due to human development and wider changes (Barras et al., 2003). By 2050, about 1300 km^2 of additional coastal land loss is projected if current global, regional and local processes continue at the same rate. There have also been significant impacts of relative sea-level rise in deltas and in and around subsiding coastal cities, in terms of increased waterlogging, flooding and submergence, and the resulting need for management responses (Nicholls et al., 2007b). The flooding in New Orleans during Katrina in 2005 was significantly exacerbated by subsidence compared to earlier flood events such as Hurricane Betsy in 1965 (Grossi and Muir Wood, 2006). In terms of response, all the major developed areas that were impacted by relative sea-level rise have been defended, even when the change in relative sea-level rise was several metres over several decades. In New Orleans, the pre-existing dike system before Katrina have been rebuilt and substantially upgraded at a cost of $15 billion over 6 years. In less developed areas, coastal retreat has occurred such as south of Bangkok where subsidence has led to a shoreline retreat of more than a kilometre.

Hence observations through the 20th Century reinforce the importance of understanding the impacts of sea-level rise in the context of multiple drivers of change – this will remain true under more rapid rises in sea level. Of these multiple drivers of change, human-induced subsidence is of particular interest, but this remains relatively unstudied in a systematic sense. Observations also emphasize the ability to protect against RSLR, especially for more densely-populated areas such as the subsiding Asian cities already discussed, or around the southern North Sea, including London and Hamburg.

FUTURE IMPACTS OF SEA-LEVEL RISE

The future impacts of sea-level rise will depend on a range of factors, including the degree to which sea-level rise accelerates, the level and manner of coastal development and the success (or failure) of adaptation (Nicholls, 2010). Assessments of the future impacts of sea-level rise have taken place on a range of scales from local to global. They all confirm potentially large impacts following Table 1, although comprehensive studies are limited and most available assessments only consider a subset of possible impacts. Taking account of population exposure, sensitivity and adaptive capacity, South and South-East Asia and Africa appear to be most vulnerable in absolute terms due to storm-induced flooding combined with sea-level rise. Small island regions in the Pacific, Indian Ocean and Caribbean stand out as being especially vulnerable to flooding (Mimura et al., 2007), even though relatively few people are affected in global terms. The populations of low-lying islands such as the Maldives or Tuvalu face the real prospect of increased flooding, submergence and forced abandonment: this perception may trigger a collapse in investment and general confidence blighting these areas and triggering abandonment long before it is physically inevitable (Barnet and Adger, 2003). An important lobby group for small islands and sea-level rise is the Alliance of Small Island States (AOSIS), which contains 37 UN votes.

However, adaptation can greatly reduce the impacts. Benefit–cost models that compare protection with retreat generally suggest that it is worth investing in widespread protection as populated coastal areas are often of high economic value (Fankhauser, 1995; Tol, 2007; Sugiyama et al., 2008). (It is worth noting that if no economic growth is assumed, protection is much harder to justify and hence the impacts of sea-level rise depend on both climate and socio-economic scenarios (Nicholls, 2004; Anthoff et al., 2010)). With or without protection, small island and deltaic areas stand out as relatively more vulnerable in most analyses and the impacts fall disproportionately on poorer countries (Anthoff et al., 2010; Sugiyama et al., 2008).

Regional and global scale assessments

Compared to national assessments, regional and global assessments provide a more consistent basis to assess the broad-scale impacts of sea-level rise.

Coastal Flooding

Globally, it was estimated that about 200 million people lived in the coastal flood plain (below the 1 in 1,000 year surge-flood elevation) in 1990, or about 4% of the world's population (Nicholls et al., 1999). Based on estimates of defence standards, on average 10 million people/year experienced coastal flooding in 1990. These numbers will change due to the competing influences of relative sea-level rise (due to local subsidence and global changes), changes in coastal population and improving defence standards as people become more wealthy (Nicholls et al., 1999). Relative sea-level rise is assumed to displace extreme water levels upwards (assuming constant storm characteristics). The analysis is designed to explore the impacts of global-mean sea-level rise if it is largely ignored. Therefore, the increasing protection standards only consider existing climate variability (i.e. surges in 1990) and the analysis is considering a world that is completely ignoring the issue of global-mean (and relative) sea-level rise. (This follows recent behaviour globally). Outputs include:

- people in the hazard zone (PHZ) – the population living below the 1 in 1,000 year flood plain (or the exposed population);
- people at risk (PAR) – the average number of people who experience flooding per year (a measure of risk that takes account of flood protection);

Table 2 illustrates the impacts of no global-mean sea-level rise and the IS92a global-mean sea-level rise scenarios on flooding (for a global-mean rise in the range 19 to 80 cm from 1990 to the 2080s). Generic results include:

- Even without sea-level rise, the number of people flooded each year first increases significantly due to increasing coastal populations (i.e., exposure), and then diminishes as increasing protection standards due to rising GDP/capita become the most important factor.
- Significant impacts of sea-level rise are not apparent until the 2050s or later so sea-level rise is a slow onset hazard.
- The uncertainty about impacts is large with relatively minor impacts for the low rise scenario in the 2080s, a 10-fold increase in PAR under the mid rise scenario and a 27-fold increase in PAR under the high rise scenario for the 2080s.

Looking at 20 world regions, they all see an increase in the incidence of flooding compared to the baseline, most especially under the higher sea-level rise scenarios. The most vulnerable regions in relative terms are the small island regions of the Caribbean, Indian Ocean and Pacific Ocean. However, absolute increases in the incidence of flooding are largest in the southern Mediterranean (largely due to the Nile delta), West Africa, East Africa, South Asia and South-East Asia – these five regions contain about 90% of the people flooded in all cases for the 2080s. This reflects the large populations of low-lying deltas in parts of Asia, and projections of rapid population growth around Africa's coastal areas. While developed country regions have relatively low impacts, sea-level rise still produces a significant increase in the number of people who would be flooded assuming no adaptation for sea-level rise. These results show that sea-level rise could have a profound impact on the incidence of flooding – the higher the total rise, the greater the increase in flood risk, all other factors being equal. Any increase in storminess would further exacerbate the predicted increase in coastal flooding.

Using the DIVA model, we can examine flood impacts with and without dike upgrade (Nicholls, 2010). No upgrade leads to results that are qualitatively similar to those in Table 2. The behaviour assuming dike upgrade is quite different and independent of the magnitude of the sea-level rise scenario, the number of people flooded is projected to decline through the 21st Century. This reflects that the dikes are raised more than the magnitude of sea-level rise as people adapt to sea-level rise and become more risk adverse as they become more wealthy. This illustrates that the success or failure of adaptation is fundamental to understanding impacts as discussed later.

Environmental Refugees

Sea-level rise is often associated with a large potential for environmental refugees forcibly displaced from their homes (Myers, 2002). Potentially, many tens or even hundreds of millions of peoples could be so displaced, especially given that coastal populations are growing significantly worldwide. However, if we can successful adapt to these challenges, this is a much smaller problem than is often assumed. Adaptation could include flood defences for urban areas, and land use planning for new developments to avoid the more risky areas. As a reference, Tol (2002a; 2002b) suggests that most coastal areas are worth protecting in a benefit-cost sense (protection costs are less than damage costs). This formulation suggests that ≤75,000 people/year will be displaced by a 1-m sea-level through the 21st Century, after allowing for protection: incrementally this is of order 1% of the potentially displaced population. This result has a large uncertainty, but it illustrates again that the success or failure of adaptation is a key element to understanding the scale of the problem.

Global Costs of Sea-Level Rise

Global estimates of the incremental costs of upgrading defence infrastructure[3] suggest the costs are much lower than the expected damage (Tol, 2007). IPCC CZMS (1990) estimated the costs of defending against a 1-m sea-level rise at $500 billion. Hoozemans et al (1993) doubled these costs to $1000 billion. Looking at the total costs of sea-level rise including dryland and wetland loss and incremental defence investment, Fankhauser (1995) estimated annual global costs of $47 billion using the IPCC CZMS (1990) data. Tol (2002a; 2002b) made similar estimates using the Hoozemans et al. (1993) data, supplemented by other data sources and adding the costs of forced migration. The protection was optimised and it was estimated that the annual costs of sea-level rise are only $13 billion/year for a 1-m global rise in sea level: much lower than estimated by Fankhauser, and much lower than widely assumed. However, any failure in protection will lead to much higher costs. Sugiyama et al (2008) noted that that the spatial distribution of infrastructure and wealth along the coast influences costs: the more wealth is concentrated the smaller the protection costs.

[3] These incremental costs should not be compared directly with projects such as the post-Katrina defence of New Orleans as they only reflect the sea-level component of these needs.

RESPONDING TO SEA-LEVEL RISE

The two potential responses to sea-level rise are mitigation and adaptation: only the latter is considered here. Adaptation to sea-level rise involves responding to both mean sea-level rise and extreme sea-level rise (Hallegatte, 2009). Planned adaptation options to sea-level rise are usually presented as one of three generic approaches (Klein et al., 2001) with examples in Table 1:

- *(Planned) Retreat* – all natural system effects are allowed to occur and human impacts are minimised by pulling back from the coast via land use planning, development control, etc.;
- *Accommodation* – all natural system effects are allowed to occur and human impacts are minimised by adjusting human use of the coastal zone via flood resilience, warning systems, insurance, etc.;
- *Protection* – natural system effects are controlled by soft or hard engineering (e.g., nourished beaches and dunes or seawalls), reducing human impacts in the zone that would be impacted without protection.

Given the large and rapidly growing concentration of people and activity in the coastal zone, autonomous (or spontaneous) adaptation processes alone will not be able to cope with sea-level rise. Further, adaptation in the coastal context is widely seen as a public responsibility. Therefore, all levels of government have a key role in developing and facilitating appropriate adaptation measures. The required adaptation costs remain uncertain, but as large amounts are already invested in managing coastal floods, erosion and other coastal hazards, the incremental costs of including global sea-level rise does not appear infeasible at a global scale over the coming decades (World Bank, 2010). However, in certain settings such as small islands, these costs could overwhelm local economies (Fankhauser and Tol, 2005; Nicholls and Tol, 2006). Another key issues are the adaptation deficit (Parry et al., 2009), and observed behaviour does not agree with the implicit model in many of the benefit-cost analysis. Lastly, maintenance can substantially raise costs compared to just capital costs, and this needs to be considered and poorly maintained flood defences are worst than no defences as the engender a false sense of security.

DISCUSSION/CONCLUDING REMARKS

The abstract illustrates that understanding the impacts of sea-level rise crosses many disciplines and embraces natural, social, and engineering sciences, and major gaps in that understanding remain. The success or failure of adaptation in general, and protection in particular, is an important issue which deserves more attention and has lead to what Nicholls and Tol (2006) termed the ‘optimistic’ and ‘pessimistic’ view of the importance of sea-level rise. The pessimists tend to focus on high rises in sea level, extreme events like Katrina, and view our ability to adapt as being rather limited resulting in alarming impacts, including widespread human displacement from coastal areas. The optimists tend to focus on lower rises in sea level and stress a high ability to protect and high benefit-cost ratios in developed areas and wonder what all the fuss is about.

The optimists have empirical evidence to support their views that sea-level rise is not a big problem in terms of the subsiding megacities that are also thriving. Importantly, these analyses suggest that improved protection under rising sea levels is more likely and rational than is widely assumed. Hence the common assumption of a widespread retreat from the shore is not inevitable, and coastal societies will have more choice in their response to rising sea level than is often assumed. However, the pessimists also have evidence to support their view. First, the socio-economic scenarios used in climate impact assessments assume substantial future economic growth and its more equitable distribution: lower growth and greater concentration of wealth in parts of the world may mean less damage in monetary terms, but it will also lead to a lower ability to protect in those poorer areas. Secondly, the benefit–cost approach implies a proactive attitude to protection with extensive management in place for the hazards of climate variability. However, experience suggests a widespread adaptation deficit in many parts of world and shows that most protection has been built as a reaction to actual or near disaster. The cost of addressing the adaptation deficit will often be significant in itself, although this has not been quantitatively assessed. If combined with high rates of sea-level rise this will probably lead to more frequent coastal disasters, even if the ultimate response is better protection. Thirdly, disasters (or adaptation failures) such as Hurricane 'Katrina' could trigger coastal abandonment, a process that has not been analysed to date. This could have a profound influence on society's future choices concerning coastal protection as the pattern of coastal occupancy might change radically. A cycle of decline in some coastal areas is not inconceivable, especially in future world scenarios where capital is highly mobile and collective action is weaker. As the issue of sea-level rise is so widely known, disinvestment from coastal areas may be triggered even without disasters actually occurring: for example, the economies of small islands may be highly vulnerable if investors become cautious (Barnett and Adger, 2003). Lastly, retreat and accommodation have long lead times – benefits are greatest if implementation occurs soon – but this is not happening widely as yet. For these reasons, adaptation may not be as successful as some assume, especially if rises in sea level are at the higher end of the range of predictions.

Thus the optimists and the pessimists both have arguments in their favour. Sea-level rise is clearly a threat, which demands a response. Scientists need to better understand this threat, including the implications of different mixtures of adaptation and mitigation, as well as the need to engage with the coastal and climate policy process so that these scientific perspectives are heard. Importantly, it has been recognised that a combination of mitigation (to reduce the risks of a large rise in sea level) and adaptation (to the inevitable rise) appears to be the most appropriate course of action, as these two policies are more effective when combined than when followed independently, and together they address both immediate and longer term concerns (Nicholls et al., 2007a).

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Table 1. The main natural system effects of relative sea-level rise, including climate and non-climate interacting factors and examples of adaptation to these effects. Some interacting factors (e.g., sediment supply) appear twice as they can be influenced both by climate and non-climate factors. Adaptations are coded: P – Protection; A – Accommodation; R – Retreat. (adapted from Nicholls and Tol, 2006; Nicholls 2010).

NATURAL SYSTEM EFFECT		INTERACTING FACTORS		ADAPTATION RESPONSES
		CLIMATE	NON-CLIMATE	
1. Inundation, flood and storm damage	a. Surge (flooding from the sea)	Wave/storm climate, Erosion, Sediment supply.	Sediment supply, Flood management, Erosion, Land reclamation	Dikes/surge barriers [P], Building codes/floodwise buildings [A], Land use planning/hazard delineation [A/R].
	b. Backwater effect (flooding from rivers)	Run-off.	Catchment management and land use.	
2. Wetland loss (and change)		CO_2 fertilisation of biomass production, Sediment supply, Migration space	Sediment supply, Migration space, Land reclamation (i.e., direct destruction).	Land use planning [A/R], Managed realignment/ forbid hard defences [R], Nourishment/sediment management [P].
3. Erosion (of 'soft' morphology)		Sediment supply, Wave/storm climate.	Sediment supply.	Coast defences [P], Nourishment [P], Building setbacks [R].
4. Saltwater Intrusion	a. Surface Waters	Run-off.	Catchment management (overextreaction), Land use.	Saltwater intrusion barriers [P], Change water abstraction [A/R].
	b. Ground-water	Rainfall.	Land use, Aquifer use (overpumping).	Freshwater injection [P], Change water abstraction [A/R].
5. Rising water tables/ impeded drainage		Rainfall, Run-off.	Land use, Aquifer use, Catchment management.	Upgrade drainage systems [P], Polders [P], Change land use [A], Land use planning/hazard delineation [A/R].

Table 2. Sea-level rise and coastal flooding of people under the IS92a sea-level rise scenarios for low, mid and high climate sensitivities – see text for definitions of People in the Hazard Zone (PHZ) and People at Risk (PAR). The population scenario assumes that population change within the coastal flood plain is double national trends. Defences are upgraded with rising GDP/capita, but do not address sea-level rise (adapted from Nicholls, 2002).

Time (years)	Sea-Level Scenario	People in the Hazard Zone (PHZ)	People at Risk (PAR)
1990	N/A	197	10
2020s	No Rise	399	22
	Low	403	23
	Mid	411	24
	High	423	30
2050s	No Rise	511	27
	Low	525	28
	Mid	550	64
	High	581	176
2080s	No Rise	575	13
	Low	605	17
	Mid	647	133
	High	702	353

Sea-Level Impacts of Climate Change

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Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis:
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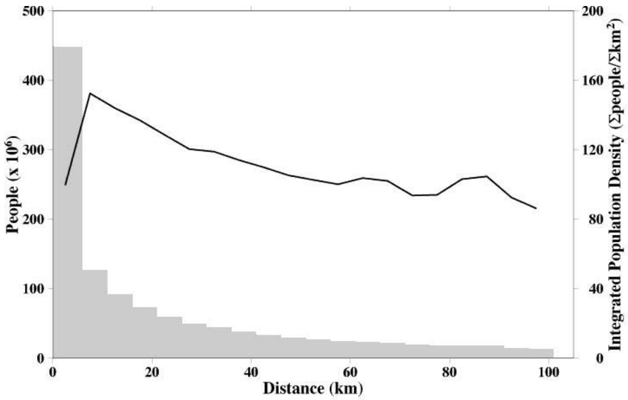
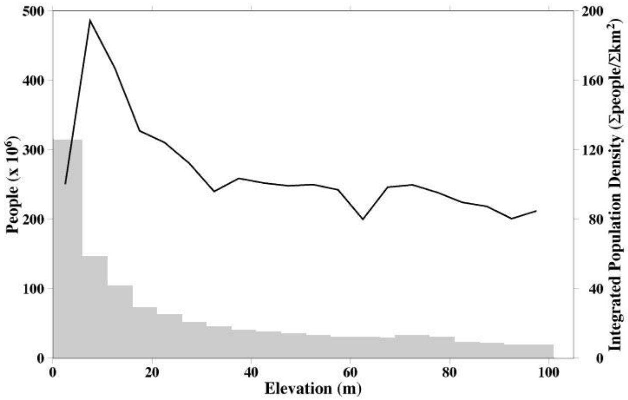
Plan

- Introduction
- What is sea-level rise?
- Impacts of sea-level rise
- Responses to sea-level rise
- Concluding thoughts

Coasts and People

Population and economic density in the coastal zone is greater than other areas of the earth's surface.

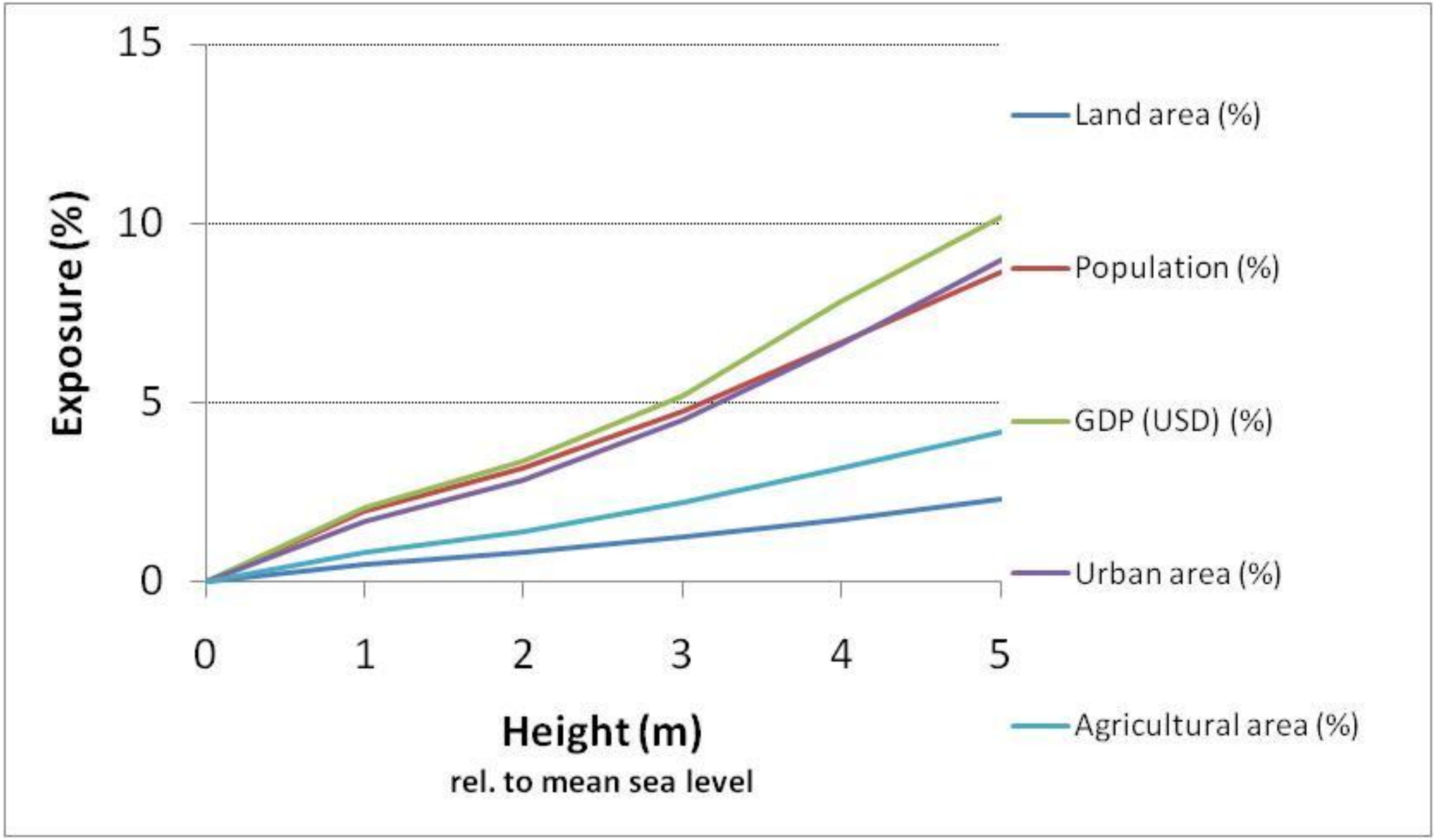




Source: Nicholls and Small, 1993, Journal of Coastal Research

Current Exposure by Elevation

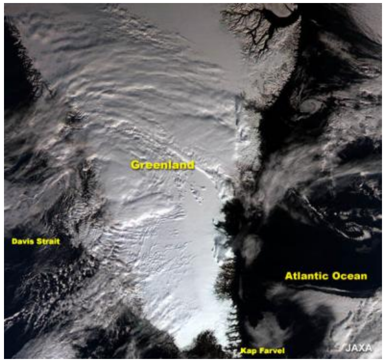
based on today's conditions in 84 developing countries



Source: Dagsputa et al (2007) World Bank Report (2009) Climatic Change

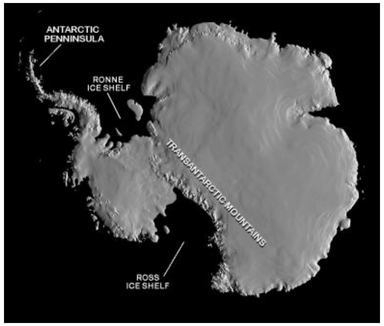
What is Sea-Level Rise?

Climate-induced Sea-Level Rise



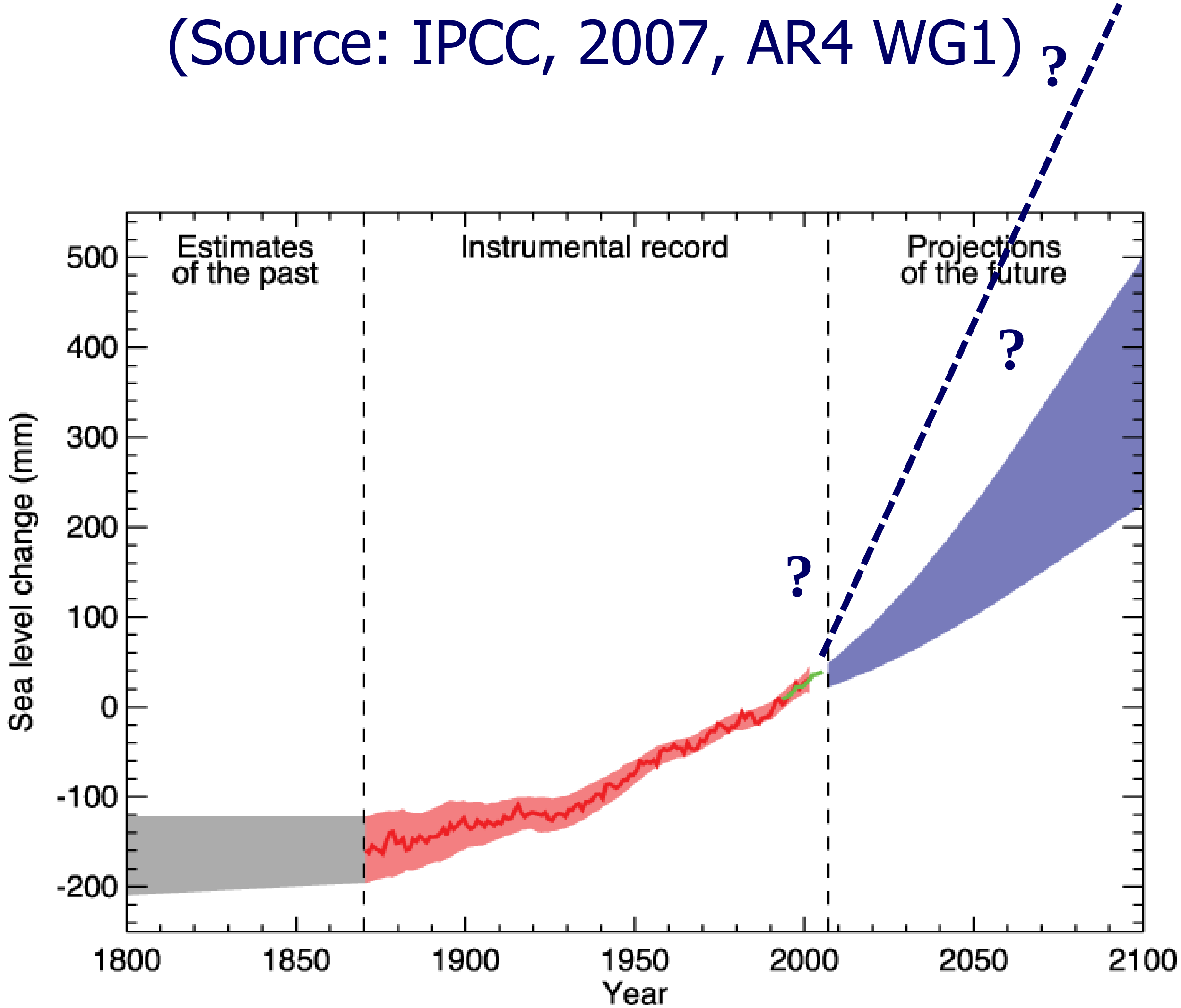
Rising temperatures lead to:

- Thermal expansion of seawater;
- Melting of land-based ice
  - Small glaciers (e.g., Rockies, Alaska)
  - Greenland ice sheet
  - West Antarctic ice sheet



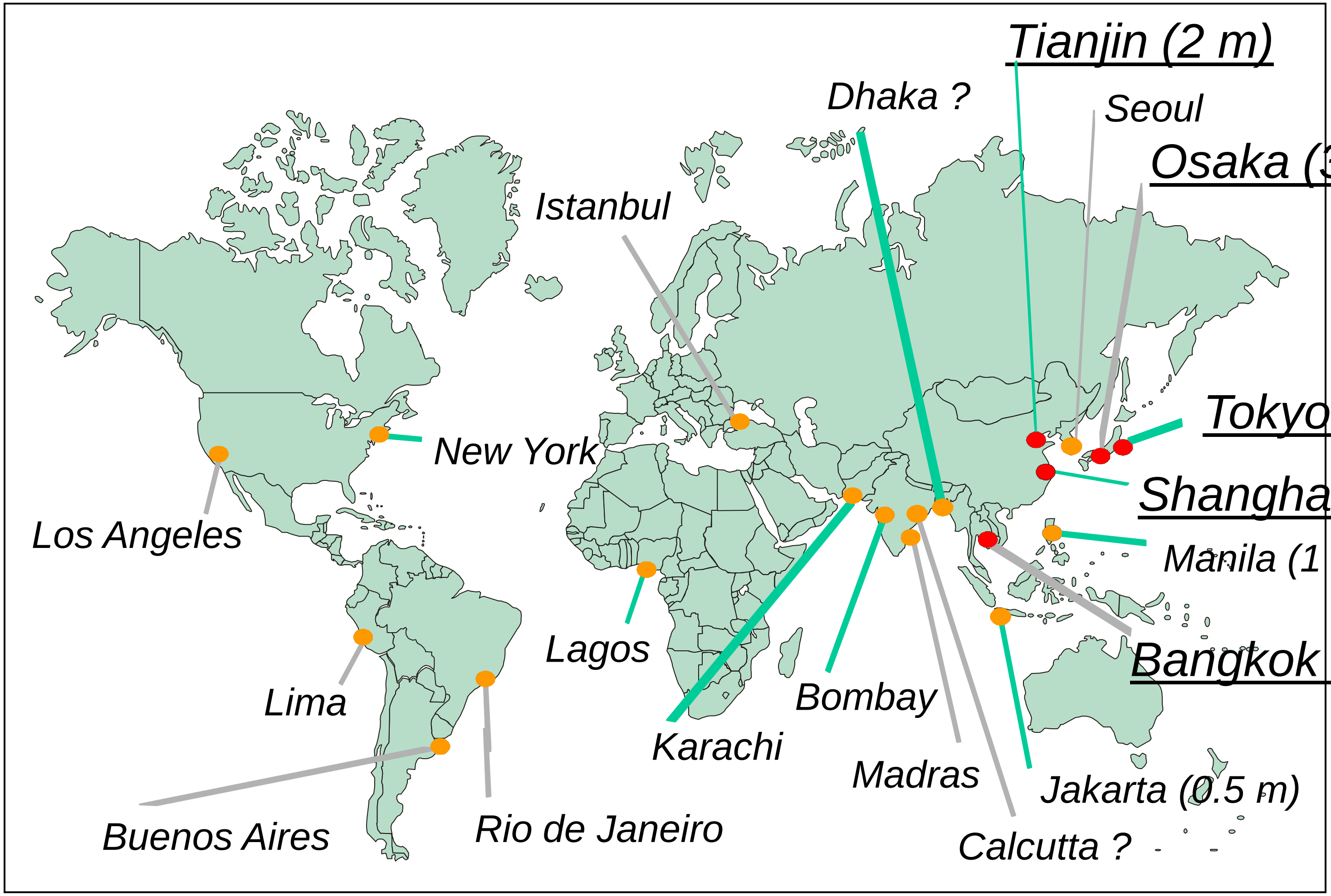
Global Sea-Level Rise

(Source: IPCC, 2007, AR4 WG1)



Subsiding Coastal Megacities

(maximum subsidence during the 20th Century)



Source: Nicholls (1995) GeoJournal

What Are The Impacts of Sea-Level Rise?

Physical Impacts of Sea-Level Rise

NATURAL SYSTEM EFFECT		INTERACTING FACTORS	
		CLIMATE	NON-CLIMATE
1. Inundation, flood and storm damage	a. Surge (flooding from the sea)	Wave/storm climate, Erosion, Sediment supply.	Sediment supply, Flood management, Erosion, Land reclamation
	b. Backwater effect (flooding from rivers)	Run-off.	Catchment management and land use.
2. Wetland loss (and change)		CO_2 fertilisation of biomass production, Sediment supply, Migration space	Sediment supply, Migration space, Land reclamation (i.e., direct destruction).
3. Erosion (of 'soft' morphology)		Sediment supply, Wave/storm climate.	Sediment supply.
4. Saltwater Intrusion	a. Surface Waters	Run-off.	Catchment management (over-extraction), Land use.
	b. Ground-water	Rainfall.	Land use, Aquifer use (over-pumping).
5. Higher water tables/ impeded drainage		Rainfall, Run-off.	Land use, Aquifer use, Catchment management.

Source: Nicholls (2010) Book on "Understanding Sea-Level Rise and Variability"

Socio-Economic Impacts of SLR

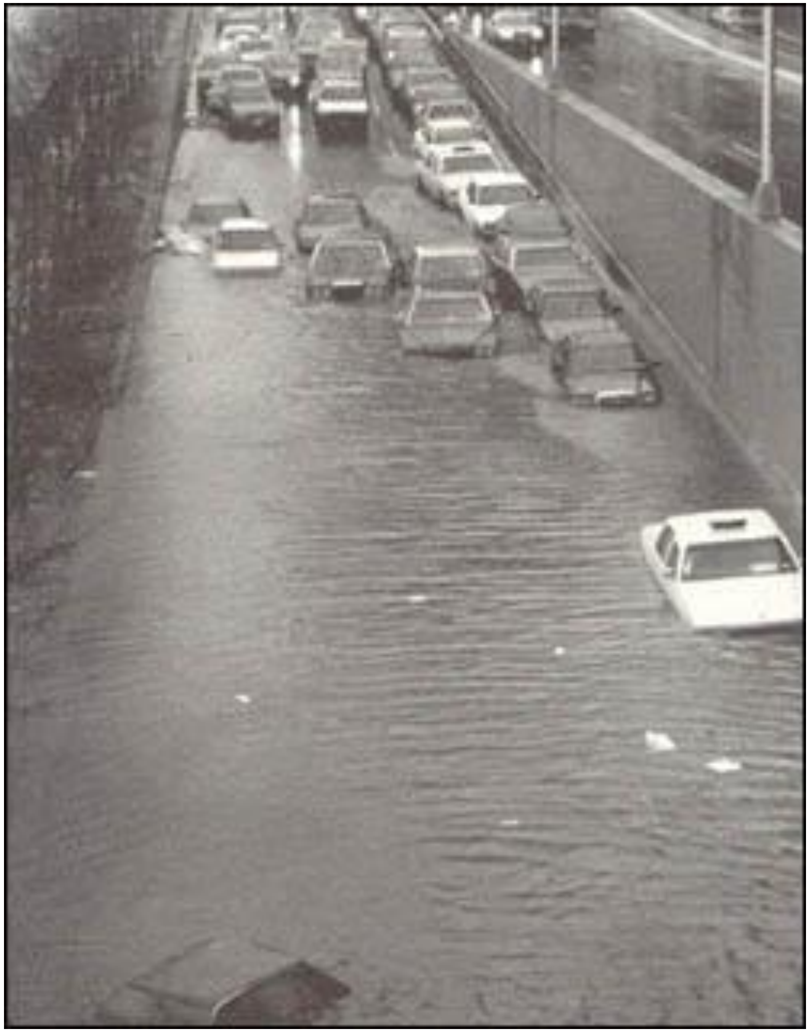
Coastal Socio-economic Sector	Sea-level rise physical impact				
	Inundation, etc.	Wetland loss	Erosion	Saltwater intrusion	Higher water tables/ etc.
Freshwater Resources	X	x	-	X	X
Agriculture and forestry	X	x	-	X	X
Fisheries and Aquaculture	X	X	x	X	-
Health	X	X	-	X	x
Recreation and tourism	X	X	X	-	-
Biodiversity	X	X	X	X	X
Settlements/ infrastructure	X	-	X	X	X

X = strong; x= weak; - = negligible or not established.

Source: Nicholls (2010) Book on "Understanding Sea-Level Rise and Variability"

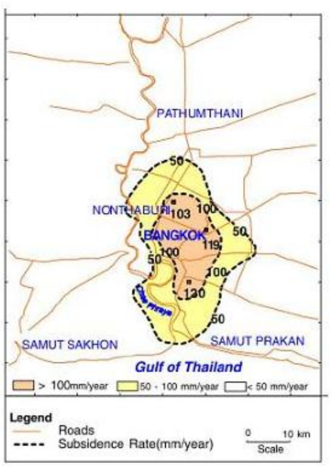
Floods: December Northeaster 1992

New York City – FDR Drive

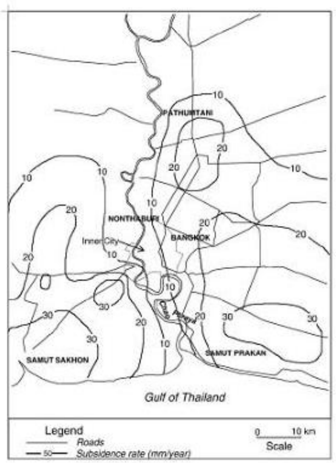


Submergence Due to Subsidence

Bangkok Area



(a) 1981

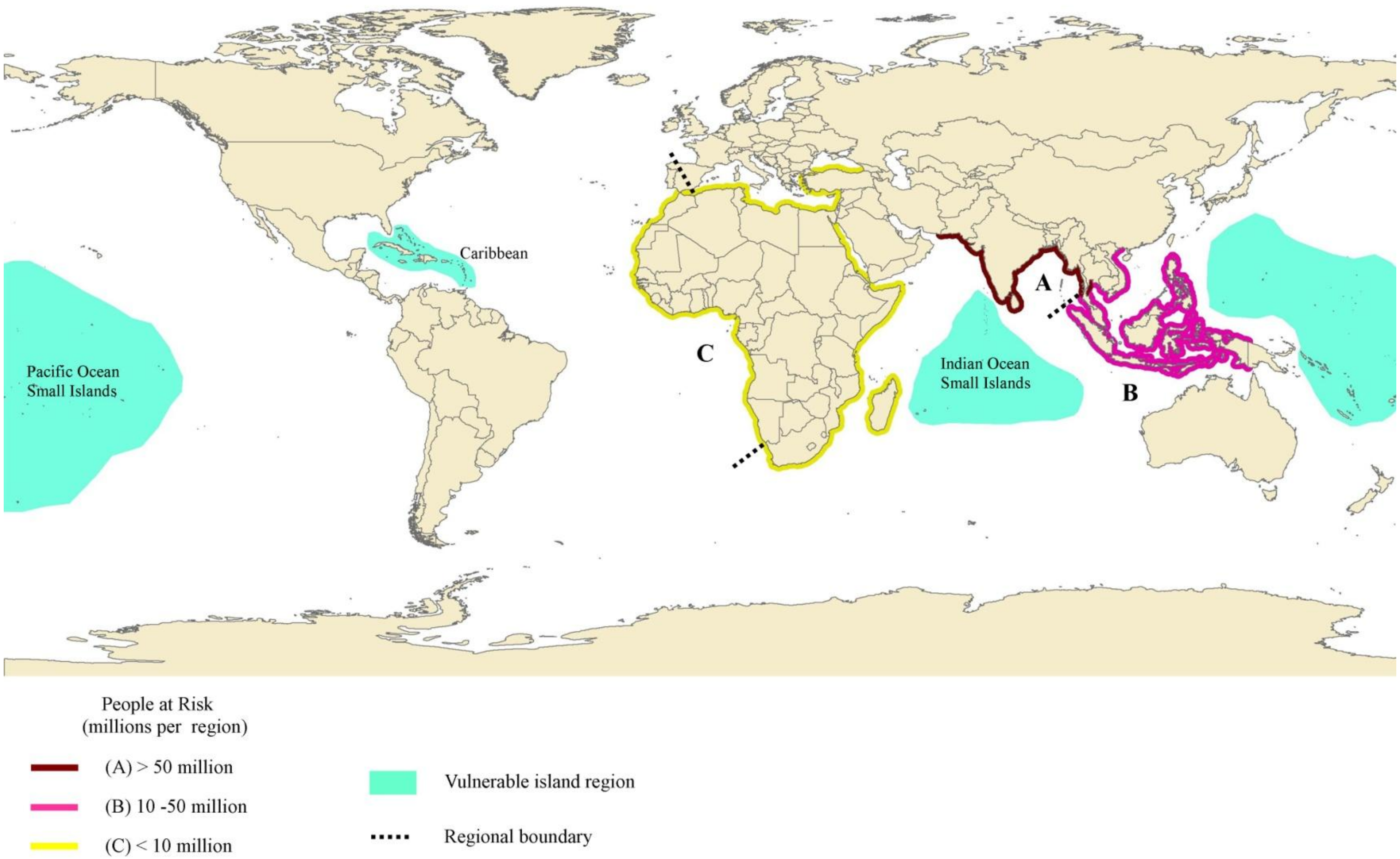


(b) 2002

Source: Phien-Wej et al (2006) Engineering Geology

Threatened Coastal Areas

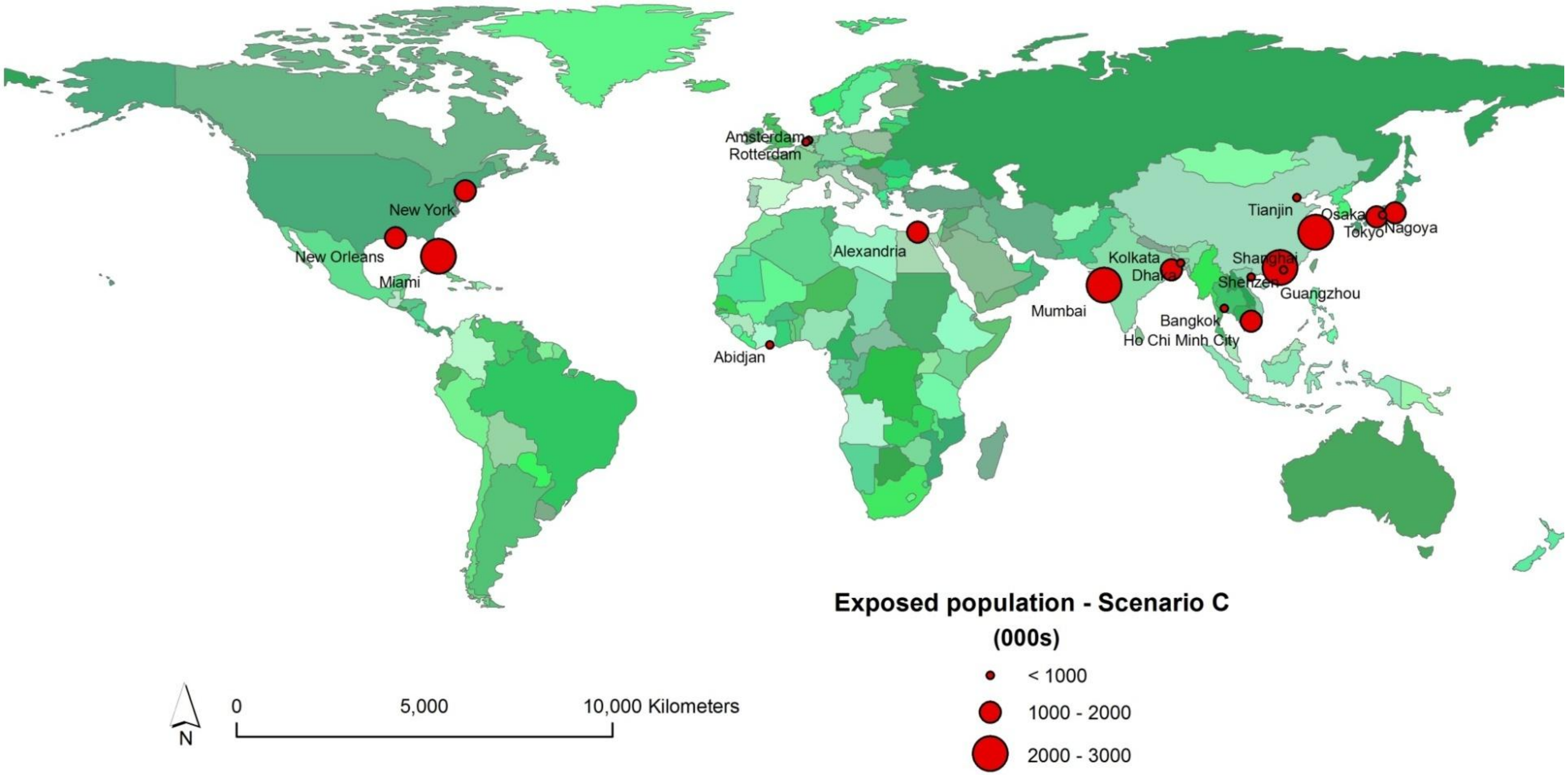
to 40-cm of SLR by the 2080s



Source: Nicholls et al. (1999); see also Nicholls (2004) Global Environmental Change

Exposed Population 2005

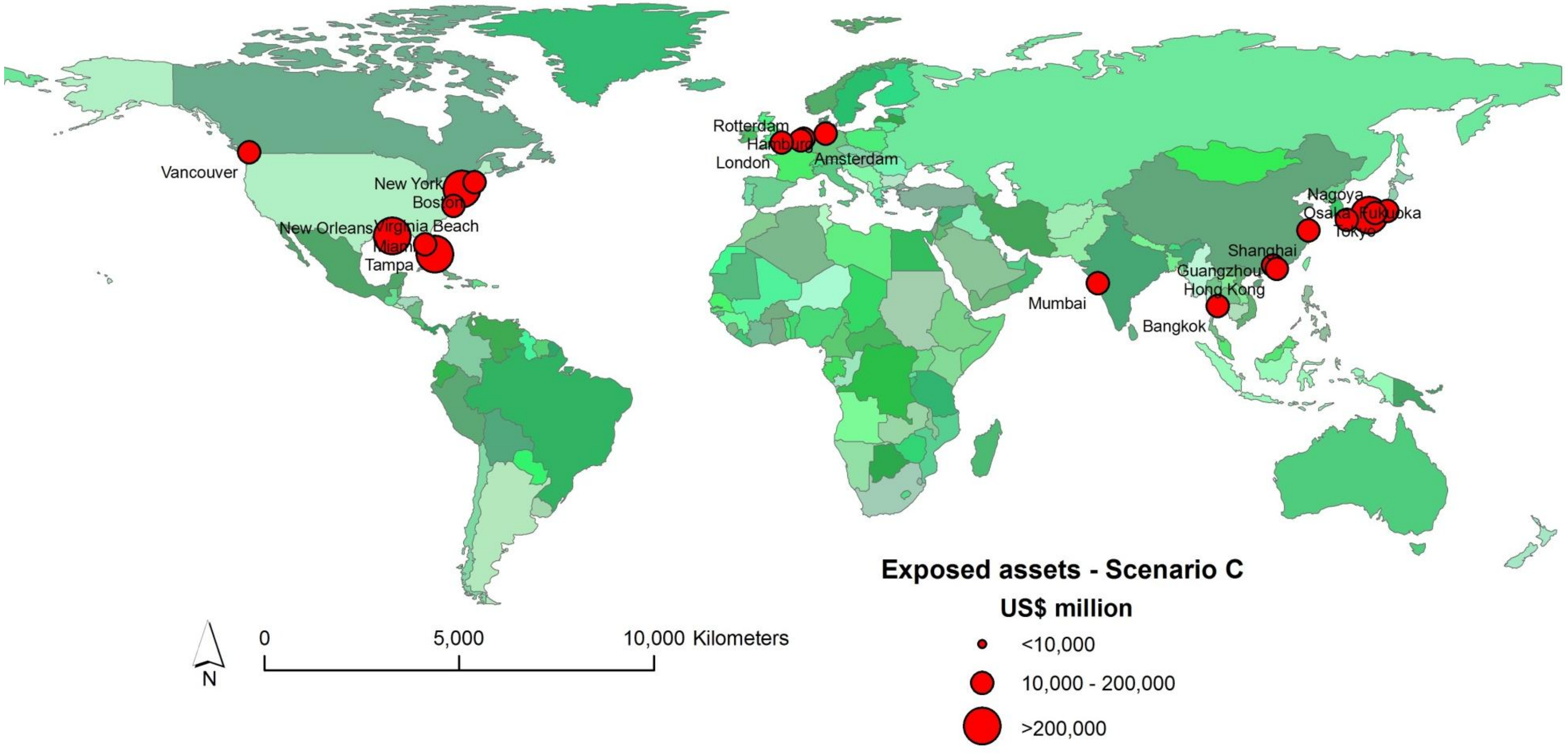
Top 20 Cities – based on 100 year flood plain



Source: Nicholls et al., 2008, OECD Report

Exposed Assets 2005

Top 20 Cities – based on 100 year flood plain



Source: Nicholls et al., 2008, OECD Report

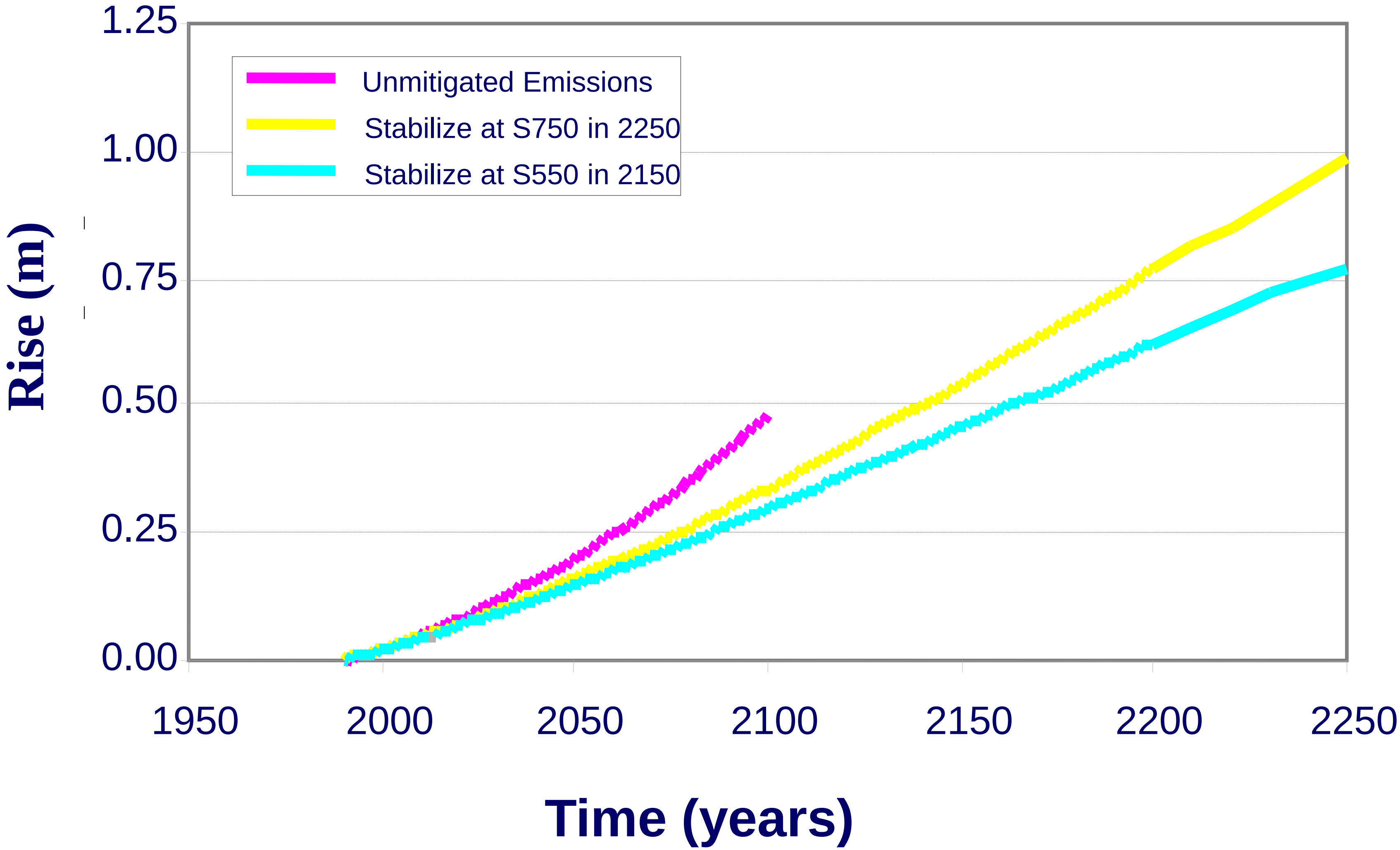
What Can We Do About Sea-Level Rise?

Mitigation – source control

Adaptation – change behaviour

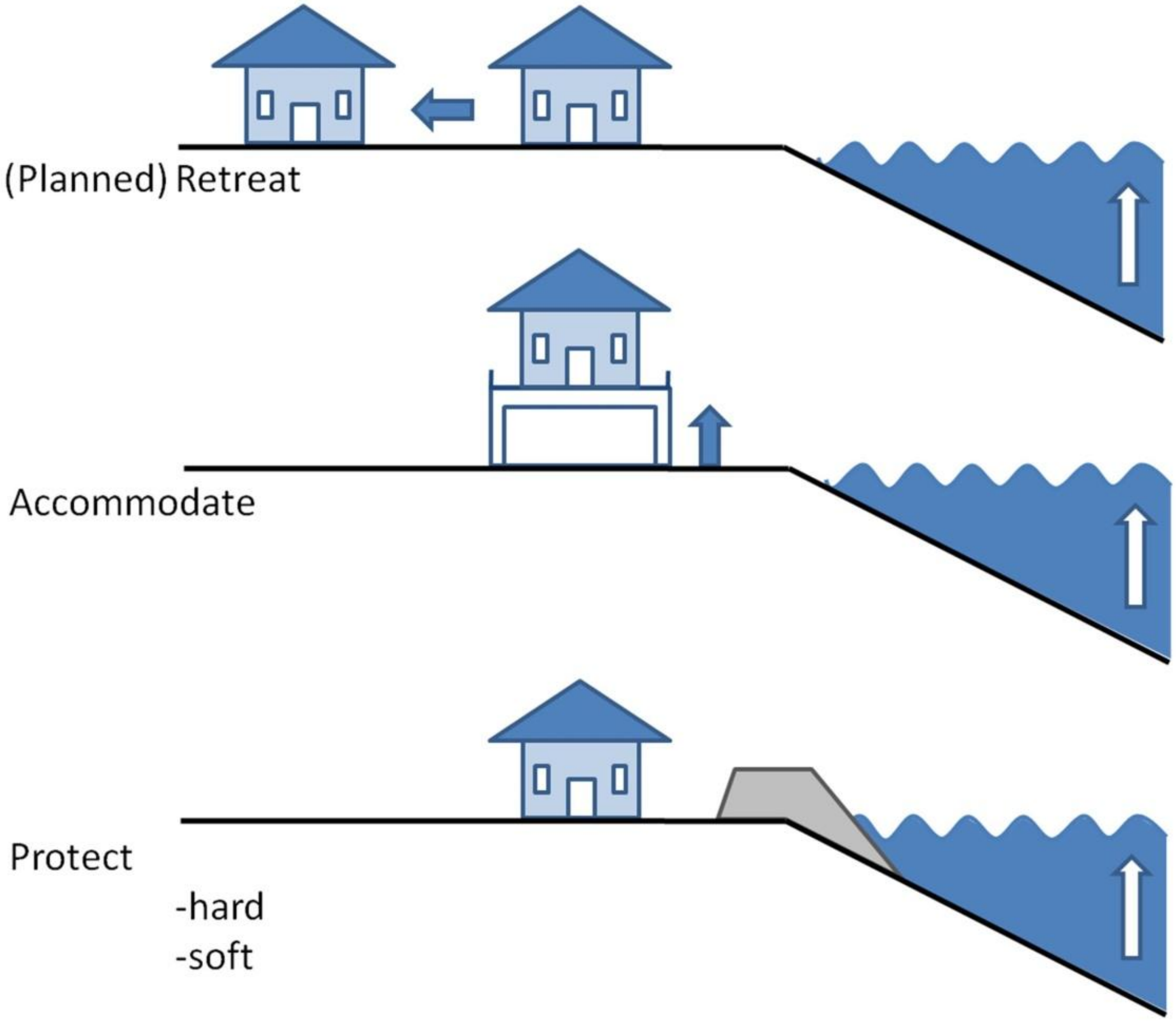
Mitigation Scenarios

Hadley Coupled Ocean-Atmosphere Model 2



Source: Nicholls and Lowe (2004) Global Environmental Change

Planned Adaptation to SLR



Source: Nicholls (2010) Book on "Understanding Sea-Level Rise and Variability"

Many Adaptation Options are Available

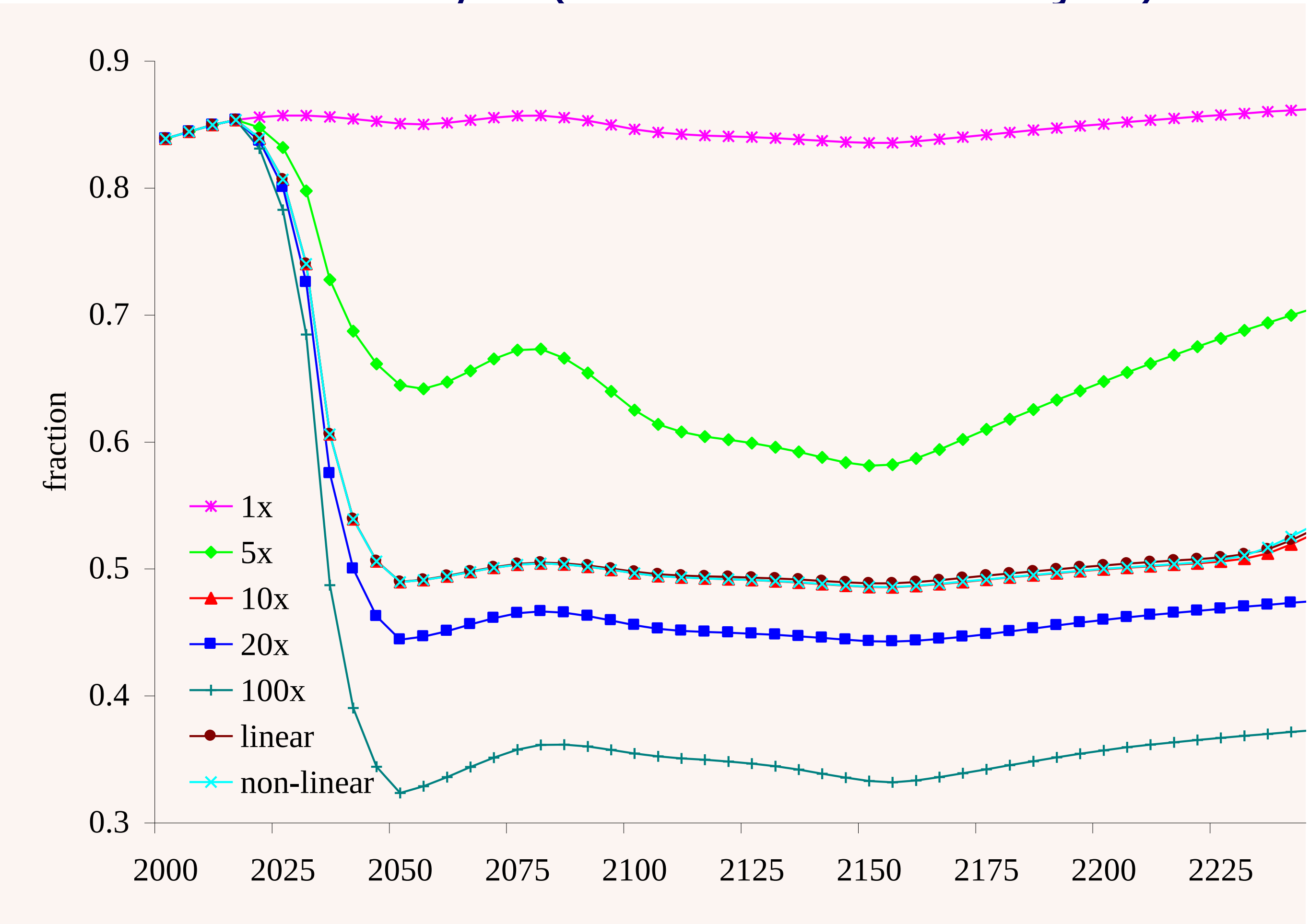
P – Protection; A – Accommodation; R – Retreat.

NATURAL SYSTEM EFFECT		POSSIBLE ADAPTATION RESPONSES
1. Inundation, flood and storm damage	a. Surge	Dikes/surge barriers [P], Building codes/floodwise buildings [A], Land use planning/hazard delineation [A/R].
	b. Backwater effect	
2. Wetland loss (and change)		Land use planning [A/R], Managed realignment/ forbid hard defences [R], Nourishment/sediment management [P].
3. Erosion (of 'soft' morphology)		Coast defences [P], Nourishment [P], Building setbacks [R].
4. Saltwater Intrusion	a. Surface Waters	Saltwater intrusion barriers [P], Change water abstraction [A/R].
	b. Ground-water	Freshwater injection [P], Change water abstraction [A/R].
5. Rising water tables/ impeded drainage		Upgrade drainage systems [P], Polders [P], Change land use [A], Land use planning/hazard delineation [A/R].

Source: Nicholls (2010) Book on "Understanding Sea-Level Rise and Variability"

Fraction of Coast Protected
Sensitivity Analysis on Protection Costs

FUND analysis (for the ATLANTIS Project)



Source: Nicholls et al (2008) Climatic Change

Optimists vs. Pessimists

Optimists	Pessimists
Possible small rise in sea level (< 0.5 m by 2100)	Possible large rise in sea level (> 1 m by 2100)
High benefit-cost ratios	Extreme events and disasters
Adaptation will work	Adaptation will fail or is unaffordable
Thriving subsiding megacities	Optimistic socio-economic scenarios
	Observed protection tends to be reactive rather than proactive – the adaptation deficit
	Disasters could trigger coastal abandonment, undermining the case for protection
	Retreat and accommodation have long lead times and need to start now

Concluding Remarks (1)

- Climate-induced sea-level rise is inevitable – the uncertainty is its magnitude.
- This will be compounded by subsidence in many densely-populated coastal areas.
- Risks are already rising, and this will continue.
- The worst-case (do nothing) impacts are dramatic.
- There are widely differing views concerning the success or failure of adaptation.

Concluding Remarks (2)

- Mitigation of climate and subsidence is needed to make the problem more manageable.
- To adapt to dynamic coastal risks, proactive assessment is required including:
  - defining the relevant drivers,
  - the potential impacts,
  - the potential adaptation responses,
  - selection of sustainable adaptation pathways.

Sea-Level Impacts of Climate Change

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Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis:
Research on Climate Change Impacts and Associated Economic Damages

January 27-28 2011, Washington, DC

THE ECONOMIC IMPACT OF SEA LEVEL RISE

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11 February 2011

Sea level rise has a range of impacts on the coast, including permanent inundation, increased flood risk, wetland loss, and saltwater intrusion. Enhanced protection of the coast would alleviate some of these impacts (e.g., flood risk), but may ameliorate others (e.g., wetland loss).

The bulk of the literature on the economic impact of sea level rise has used the so-called direct cost method to estimate the total welfare loss. This method is conceptually straightforward. One starts with estimates of the physical impacts, estimates the price, multiplies the two, and adds the results across impacts, space and time.

While conceptually straightforward, there are practical difficulties. The price of permanent inundation, for instance, is the average value of land. Although beach front property is considerably more expensive than property further inland, sea level rise would shift the coastline. Beach front property would get lost, but adjacent property would become beach front and thus appreciate in value. The appropriate value of land is therefore the average value of land. But where would one get an estimate of the average value? Some countries have a well-developed market for land and a robust administration that collects and reports such data. Most countries, however, lack either or both.

Figure 1 shows one attempt to fill the data gap. It assumes that land value is a function of income density ($/yr/ha) – the product of per capita income ($/p/yr) and population density (p/ha). The income density elasticity of land value is estimated using data for the states of the USA. The US average land value is used as the basis for extrapolation to the rest of the world. Figure 1 contrasts this estimate to two other, equally crude attempts which agree on the broad picture but disagree on the details.

There are different issues with the cost of coastal protection. Dikes, seawalls, groins, etc are often built in the same way around the world, and often by the same small group of multinational companies. While estimates are available for the cost of raising a kilometer of dike by one meter, say, the analysis is complicated by the fact that different places would opt for different types of coastal protection.

Wetlands impose yet another challenge. There is a market price for land and for coastal protection. There is no market for wetlands. One therefore has to rely on non-market valuation techniques. Brander et al. conduct a meta-analysis of wetland values. Figure 2 reproduces some of their results, which confirm expectations. Wetlands are more valuable in places where there are many people and where there are rich people; larger wetlands are less valuable, per hectare, than smaller wetlands. At the same time, Figure 2 reveals a large range of wetland values. This is partly because wetlands are very heterogeneous, and partly because non-market valuation is difficult and prone to measurement error.

One cannot study the impacts of sea level rise (or any other aspect of climate change for that matter) without adaptation. Some forms of adaptation are trivial. Sunbathers are unlikely to return to a beach, or the beach that their grandfather used to frequent, if it would be washed away. There is no risk that sea level rise would drown them. Coastal protection, on the other hand, is typically regarded as a collective or public good.

One could take one of two approaches to model and protect coastal protection. One could study the type and design standard of coastal protection as it is. This is hampered by poor data. Attempts to gather data on the design standard of dikes and seawalls have led nowhere, even for data-rich and well-organized places like the European Union. Instead, one could study the frequency of floods. Data are available – cf. Figure 3 – but while multiple regression analysis reveals certain patterns – richer, more egalitarian, more authoritarian countries are less vulnerable to natural disasters – a substantial part of the variance cannot be explained.

The second approach to modeling coastal protection is to consider optimal adaptation. This approach circumvents the problem of collecting data on how people adapt, but it creates a counterfactual set of data on how people should adapt. There are a few studies that compare actual and optimal coastal protection. These studies suggest that decisions about coastal protection are typically not based on a cost-benefit analysis. Nonetheless, optimal adaptation is the method most prevalent in the literature.

Figure 4 shows some results for direct cost estimates. Figure 4 displays the fifty most vulnerable countries in 2100 – that is, the countries with the highest total cost relatively to their gross domestic product. While sea level rise would cost more than 0.5% of GDP in a handful of countries, the relative cost is much smaller than that in the vast majority of countries. The main reason for this result is that the absolute cost of coastal protection is stable over time, and therefore falls relative to the value of land and the size of the economy. As a result, a greater share of the coastline is protected and the relative costs of sea level rise fall. Exceptionally vulnerable are countries with a coast that is long relative to the hinterland – that is, small islands – and poor countries in river deltas.

Direct costs are conceptually straightforward albeit uncertain in practice. Direct costs, however, are only an approximation of the true impact of sea level rise on welfare. Particularly, a loss of land would reduce production in agriculture, which would drive up food prices and leave less money for other consumption. Coastal protection would increase the demand for construction and for investment funds. In order to fully appreciate the economic implications of sea level rise, one would need to use a computable general equilibrium model.

Figure 5 shows the results of such an analysis. In the scenario, it is assumed that there is no additional coastal protection. The analysis is done for assumptions that may reflect the economy of 2050, and sea level is assumed to rise by 25 cm. Two shocks are considered. First, only land is lost. Second, both land and the capital on that land are lost. In the first shock, people anticipate sea level rise and fully depreciate their houses, factories, roads etc before they are washed away by the waves. In the second shock, there is no anticipation of sea level rise. Economic activity falls if productive assets are lost to the sea. Developed economies respond little to a reduction in the availability of land but more strongly to a loss of capital; less developed economies respond in the opposite way. This reflects the relative land- and capital-intensity of production.

Figure 6 shows results from the same model and analysis, now assuming that all vulnerable and inhabited coasts are fully protected. Two mechanisms explain the pattern in Figure 6. First, coastal protection stimulates the economic activity through an increased demand for construction. (This also illustrates that GDP is a poor indicator for welfare.) Second, the increase in the demand for investment and hence savings suppresses consumption. Therefore, the impact of coastal protection is net positive in regions that have a lot of coast to protect (Australia, Canada, Russia) and it is net negative in regions that finance a lot of international investment (European Union, Japan – the model is calibrated to data from the mid-1990s).

Figure 7 compares direct cost estimates to the true welfare impact (or rather, the Hicksian equivalent variation), considering a scenario without additional coastal protection. Figure 7 reveals that, globally, the direct cost estimate underestimates the true welfare loss, but only by 15% or so. Direct costs are necessarily lower than welfare, because a loss of a productive asset deflates the entire economy and raises production costs everywhere. The direct costs only include the direct implications. Figure 7 further shows that the regional pattern of impacts is different. In some regions, the true welfare loss may be lower than the direct cost estimate. In this case, that is because relatively land-abundant regions (Brazil, Ukraine) can take advantage of land loss elsewhere and increase their agricultural production and export.

Although sea level rise is one of the better understood impacts of climate change, the above review suggests that current impact estimates leave much to be desired. There is a paucity of high-quality data. Partly, this is because not much of an effort has been made (e.g., land values). Partly, this is because good data is expensive to collect (e.g., wetland values). Partly, this is because most of the impact will take place in the future and studies necessarily rely on extrapolation. Two big uncertainties are the value of wetlands and the nature and intensity of coastal protection. Two unquantified unknowns the impact of saltwater intrusion and the effect of change in the frequency, direction, and intensity of storms.

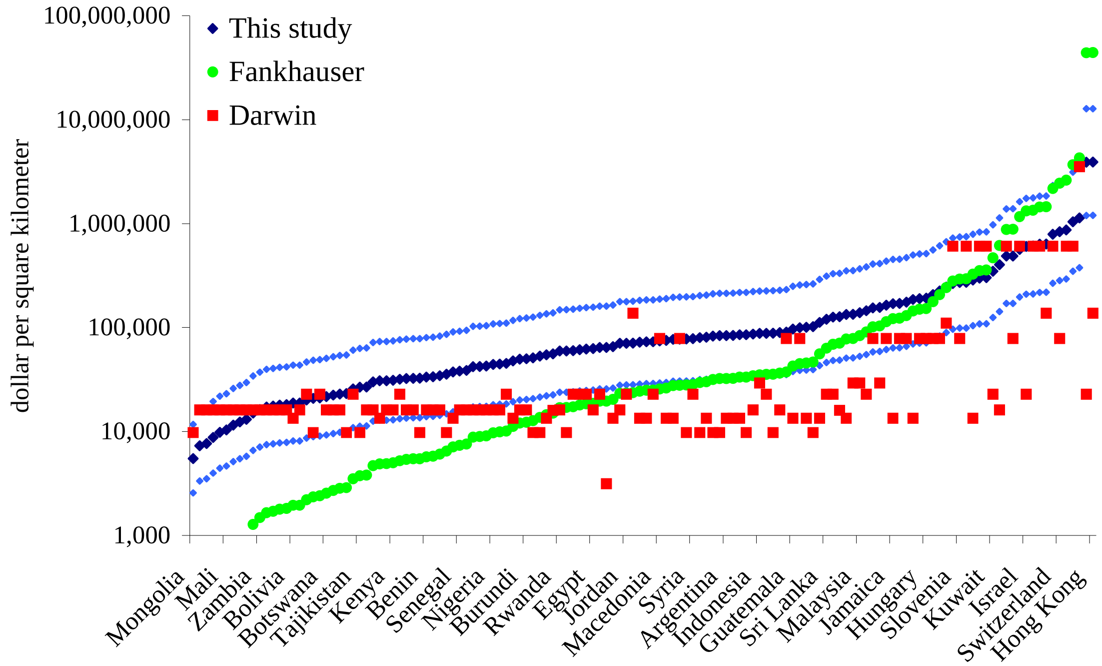

Figure 1. Three alternative estimates of the national average value of agricultural land.

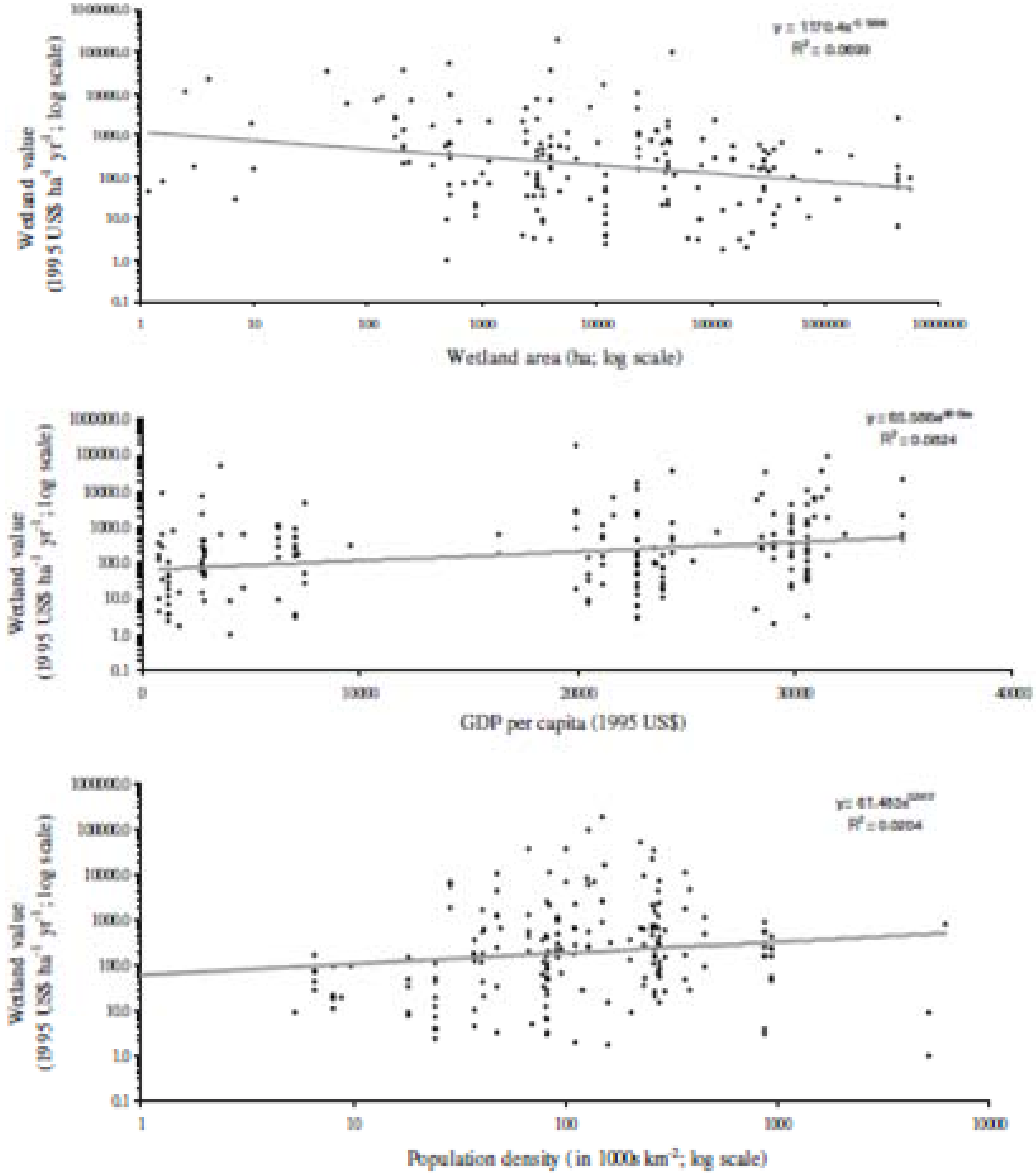

Figure 2. The value of wetlands as a function of wetland area (top panel), per capita income (middle panel) and population density (bottom panel).

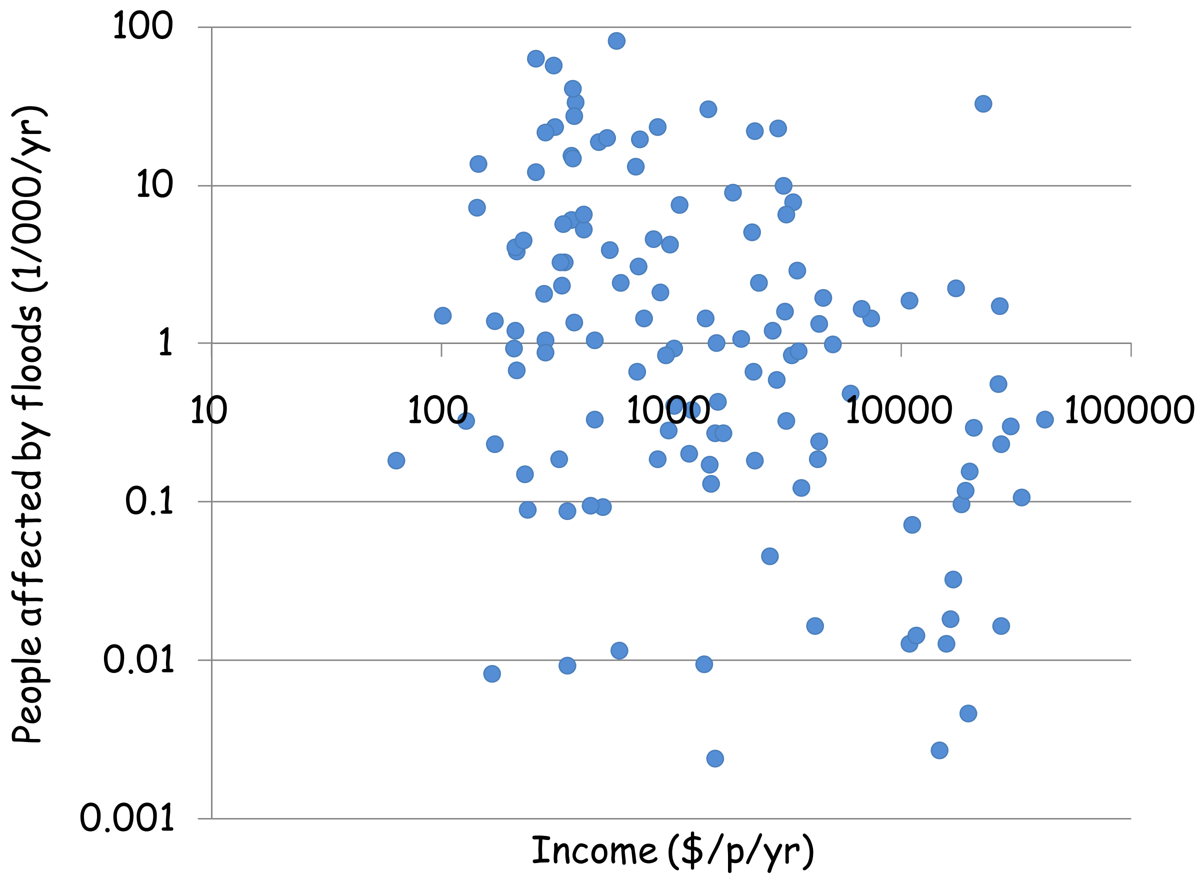

Figure 3. The number of people affected by floods as a function of per capita income.

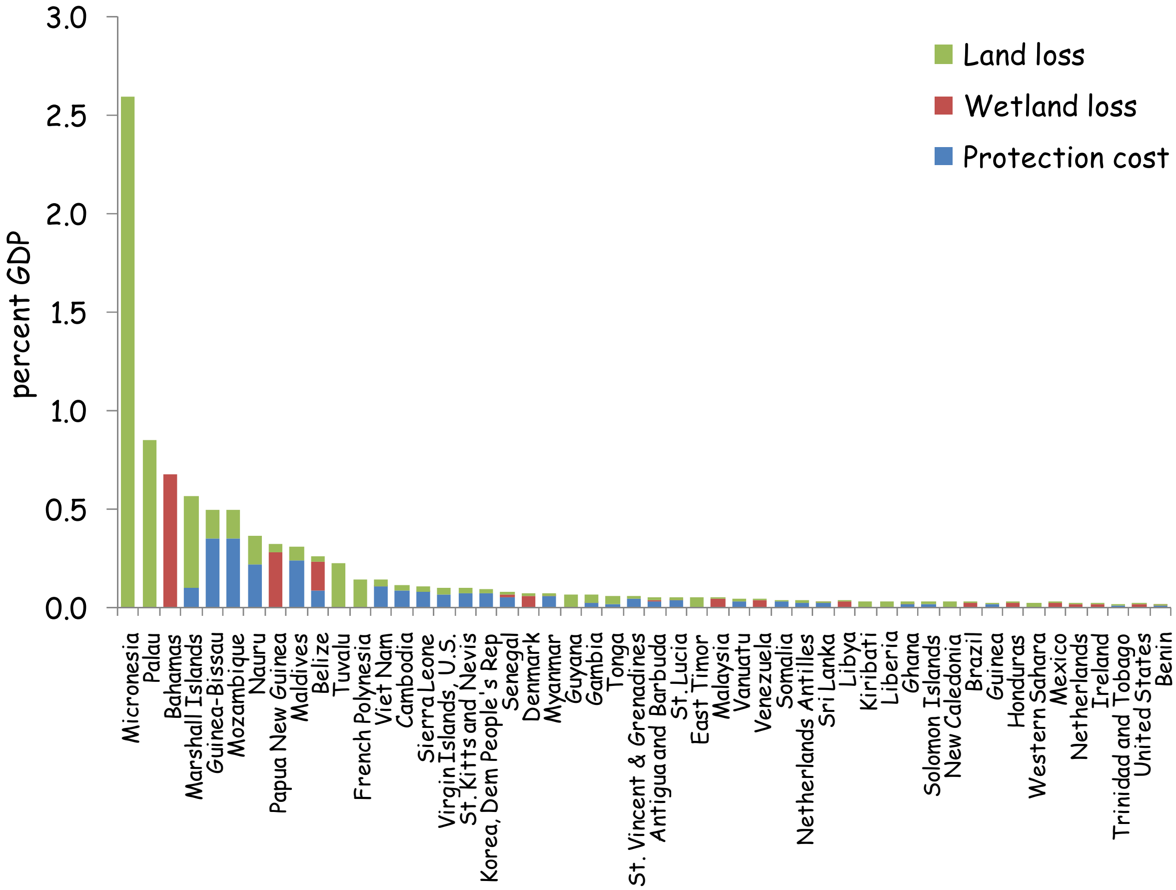

Figure 4. The fifty countries most vulnerable to sea level rise in 2100, and the composition of the annual cost.

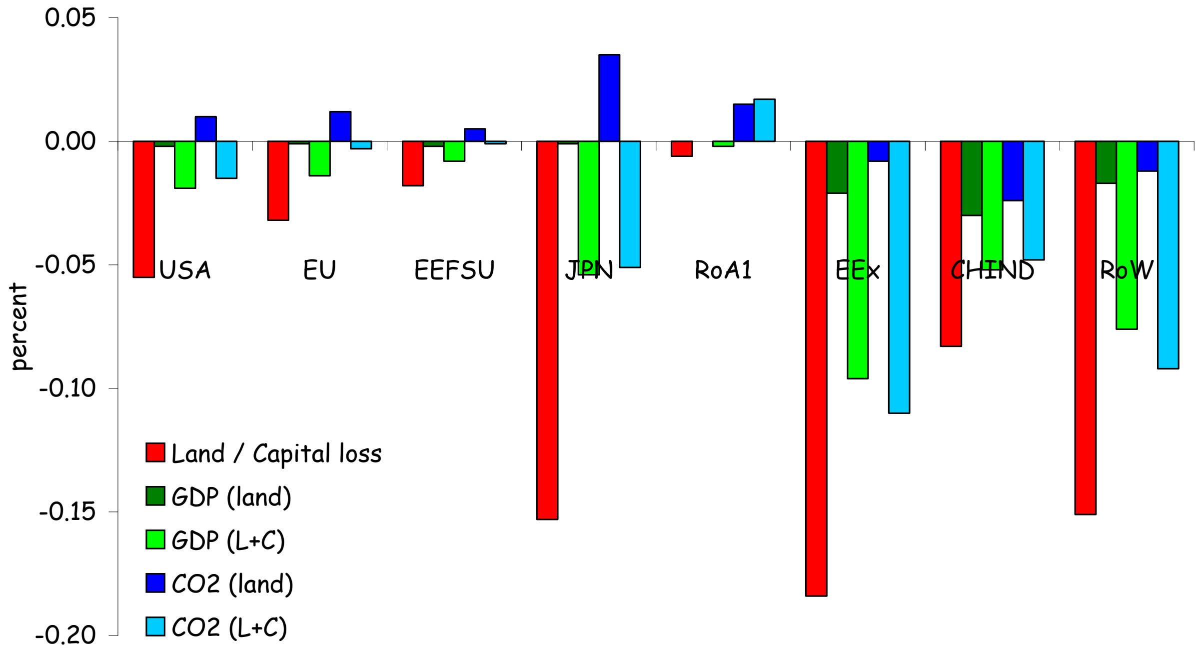

Figure 5. The impact of sea level rise (without additional coastal protection) in 2050 on GDP and CO_2 emissions.

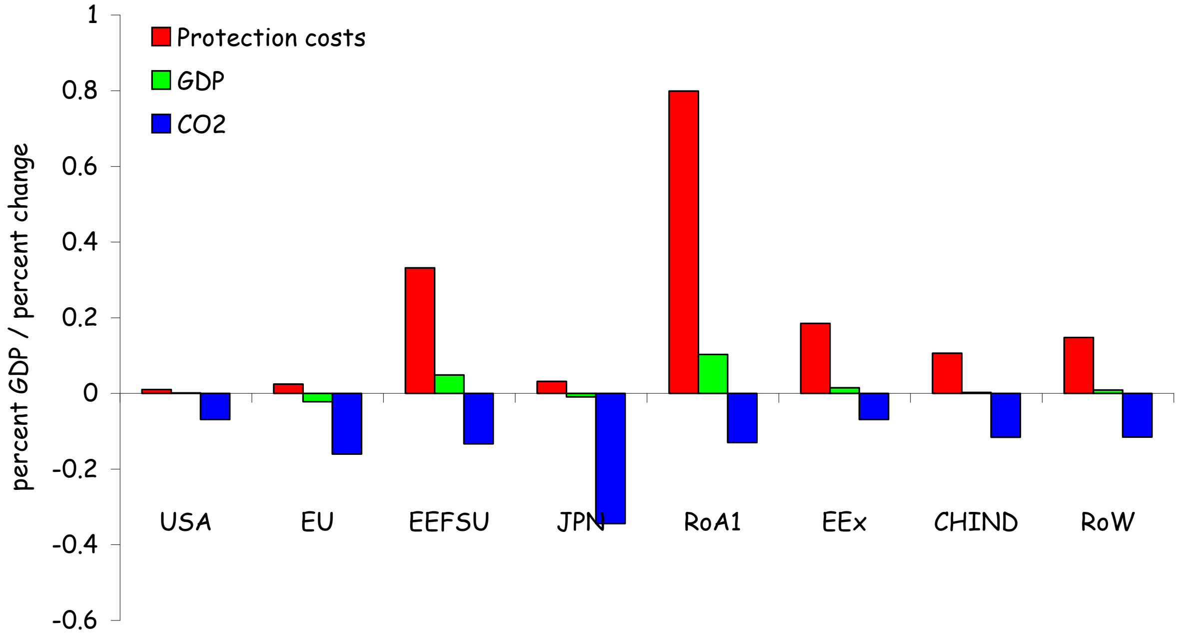

Figure 6. The impact of additional coastal protection to cope with sea level rise in 2050 on GDP and CO_2 emissions.

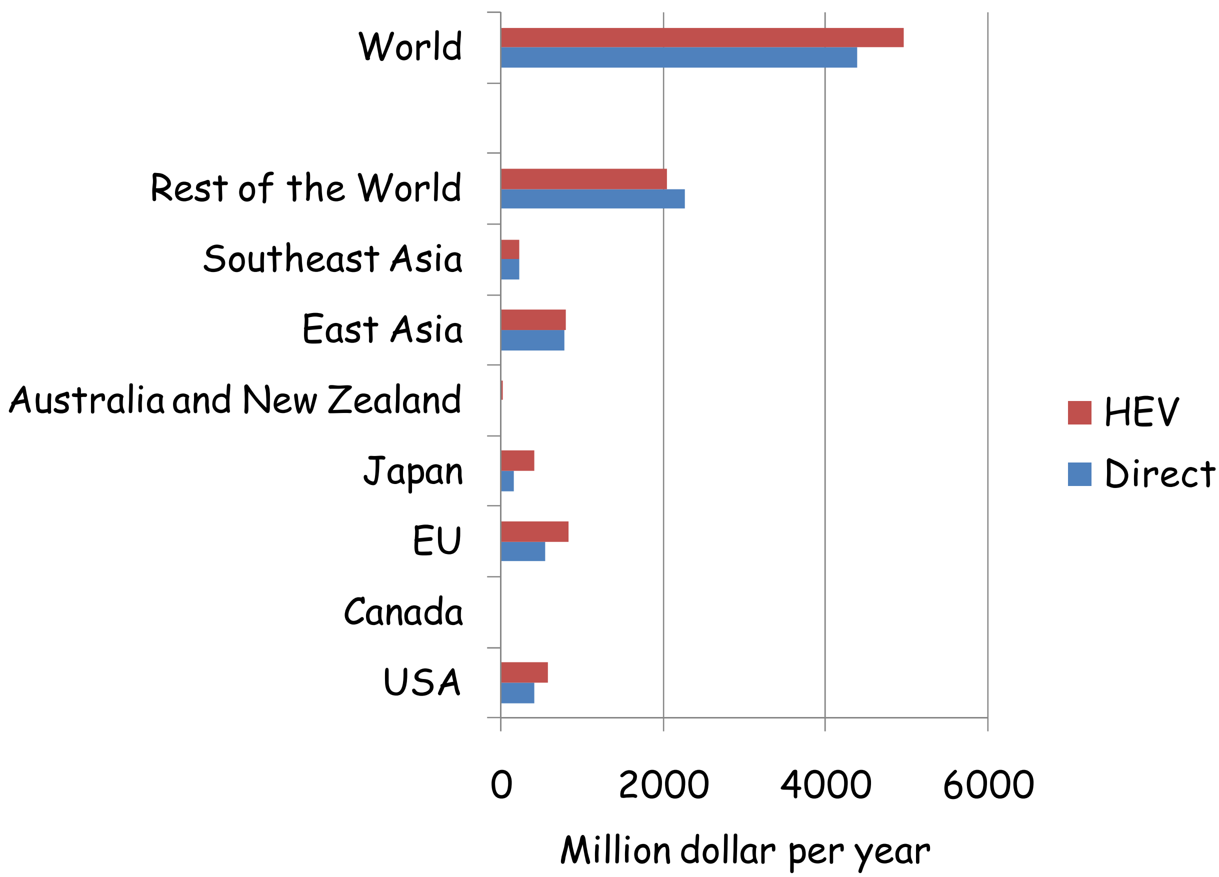

Figure 7. The direct costs and total welfare impacts of sea level rise in 2050.

Sea Level Rise' Economic Impact

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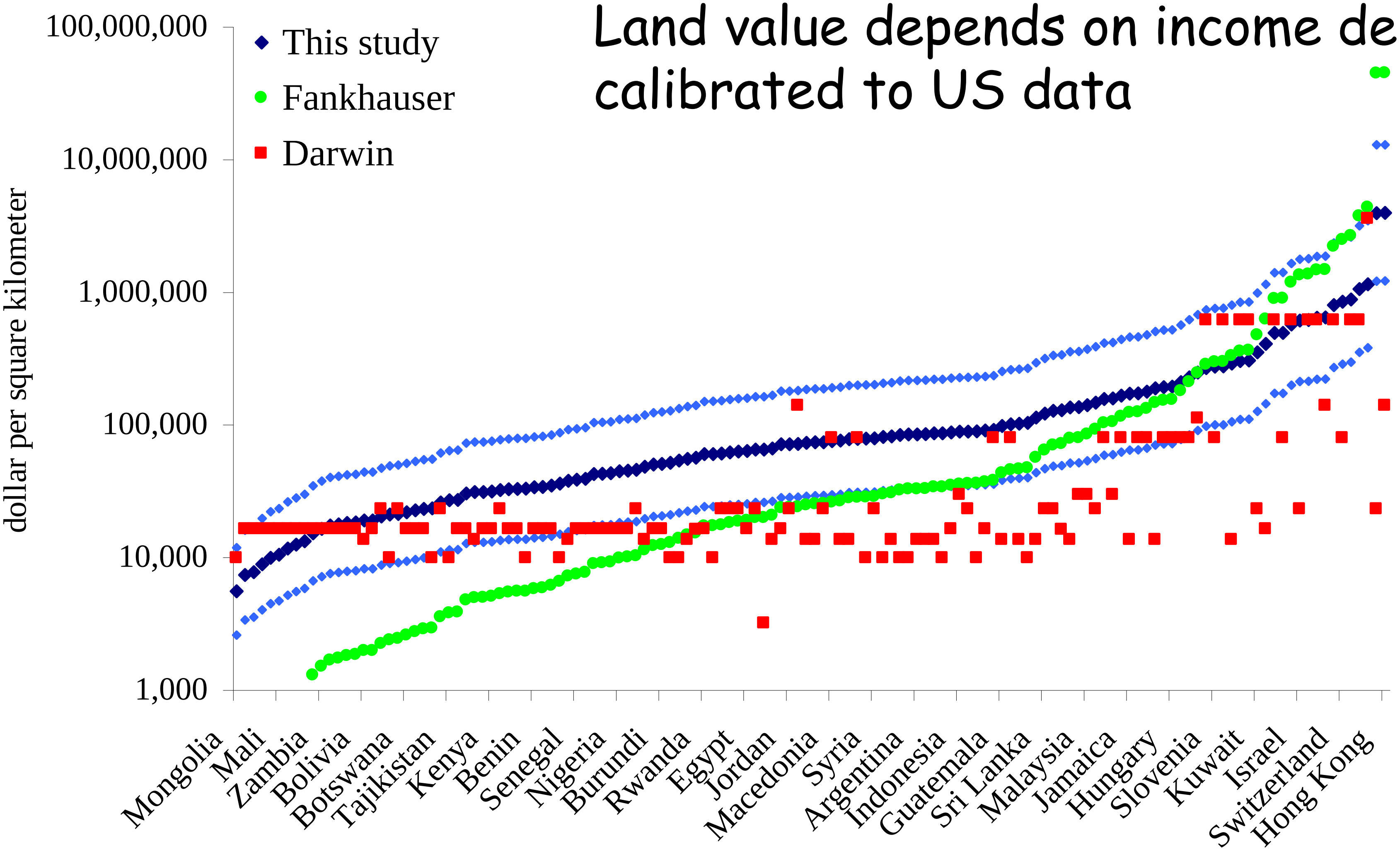
Introduction

- Prof Nicholls discussed the impact of sea level rise on the coast
- I will discuss the economic implications, focussing on
  - direct costs
  - adaptation
  - general equilibrium effects

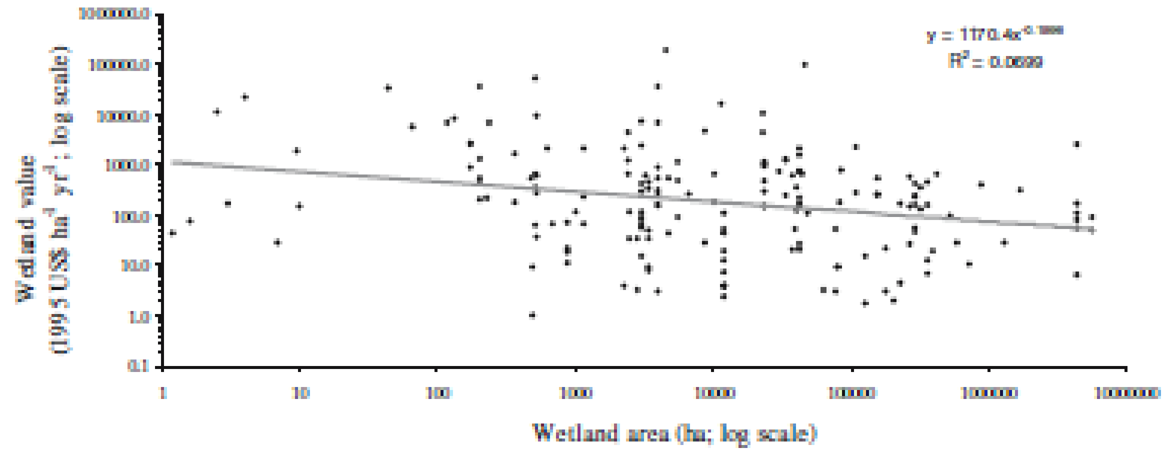
Direct costs

- Sea level rise has a number of impacts
  - Inundation / land loss
  - Flood frequency
  - Wetland loss
  - Coastal protection
  - Saltwater intrusion
  - …
- For each of each, you can estimate a unit cost and multiply that with the impact estimate of the previous presentation
- The sum is the direct cost

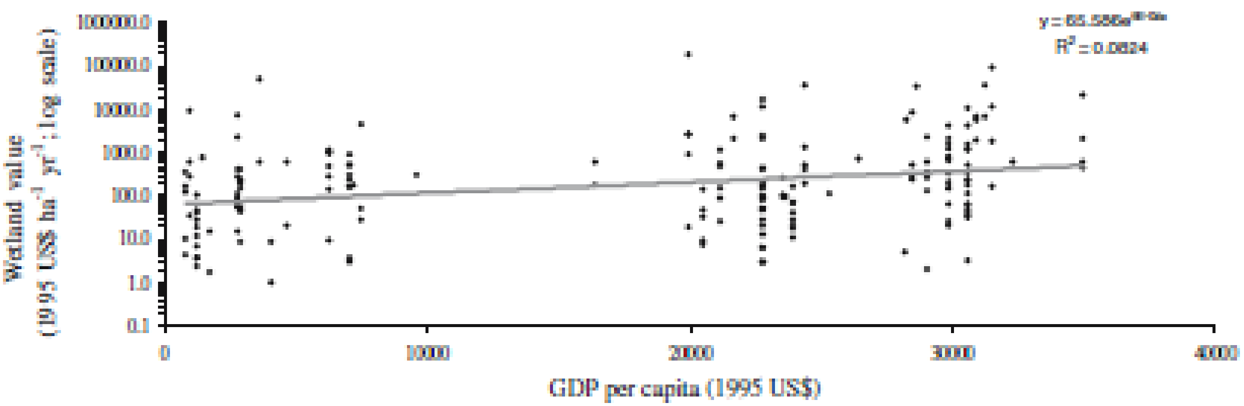
Land value depends on income density calibrated to US data



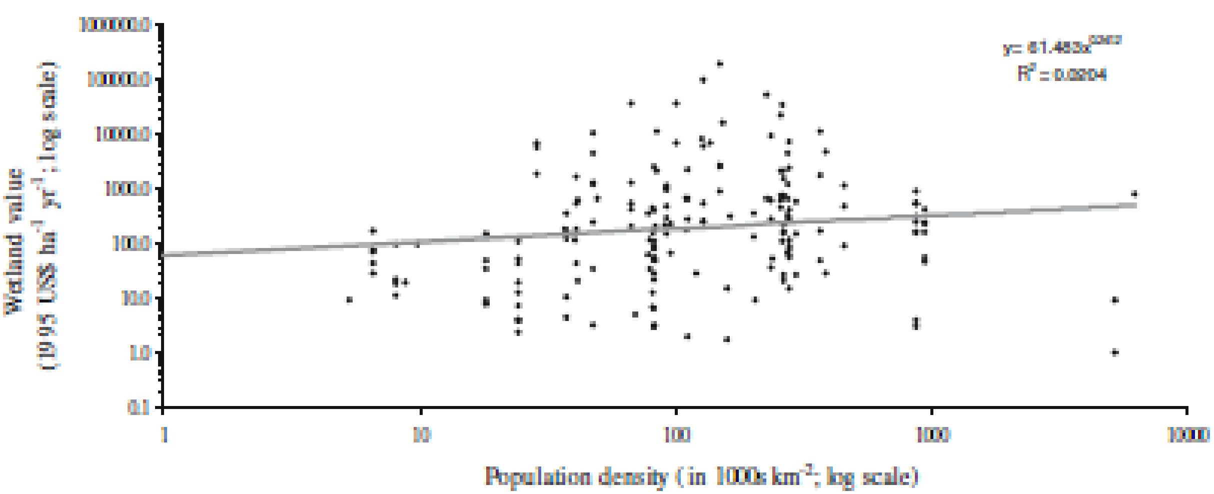
Use average values rather than beach front values as property markets will adjust to coastal realignment



Smaller wetlands command higher price per acre



Wetlands in richer countries are more valuable

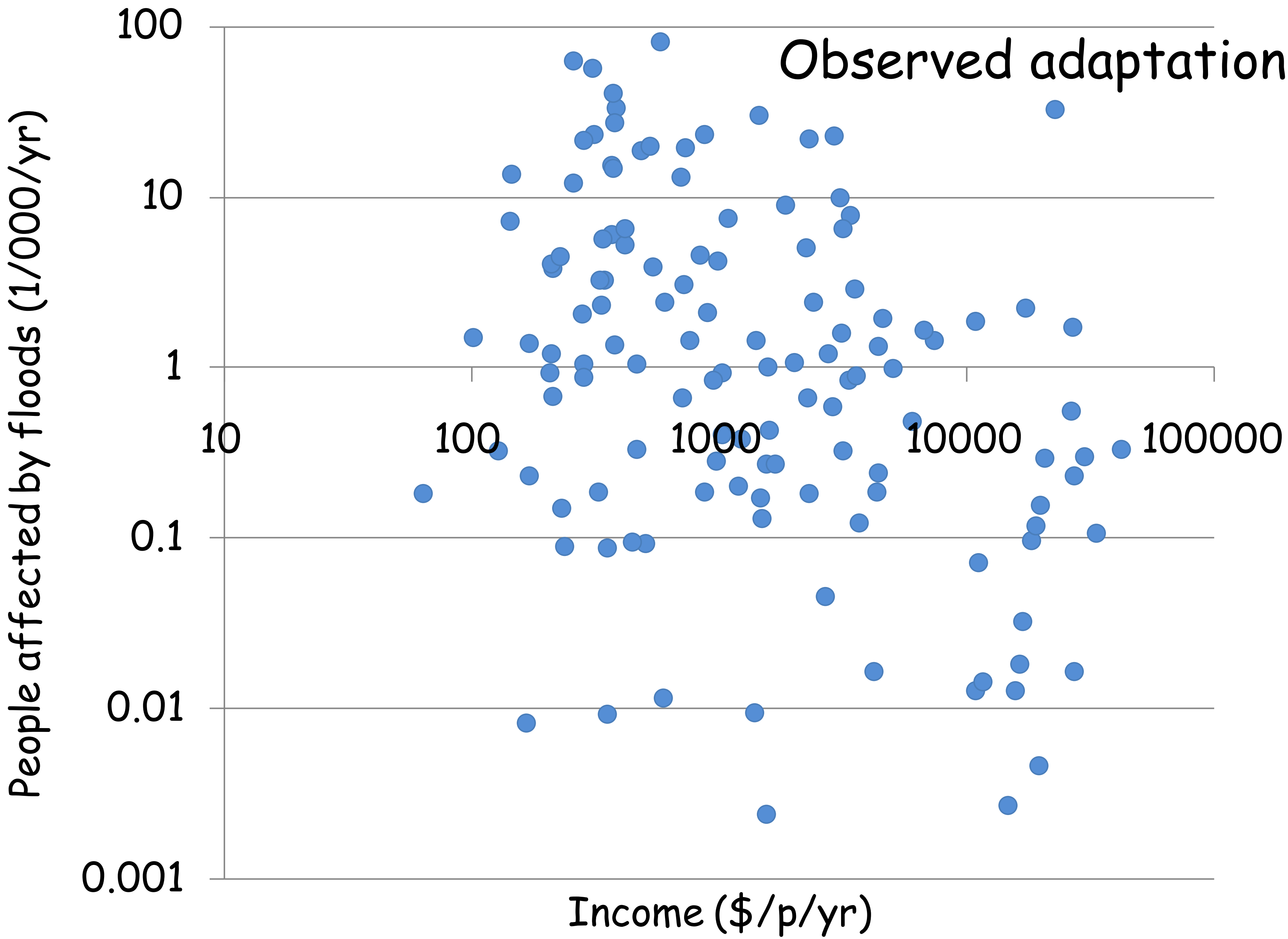


Wetlands in more densely populated countries are more valuable

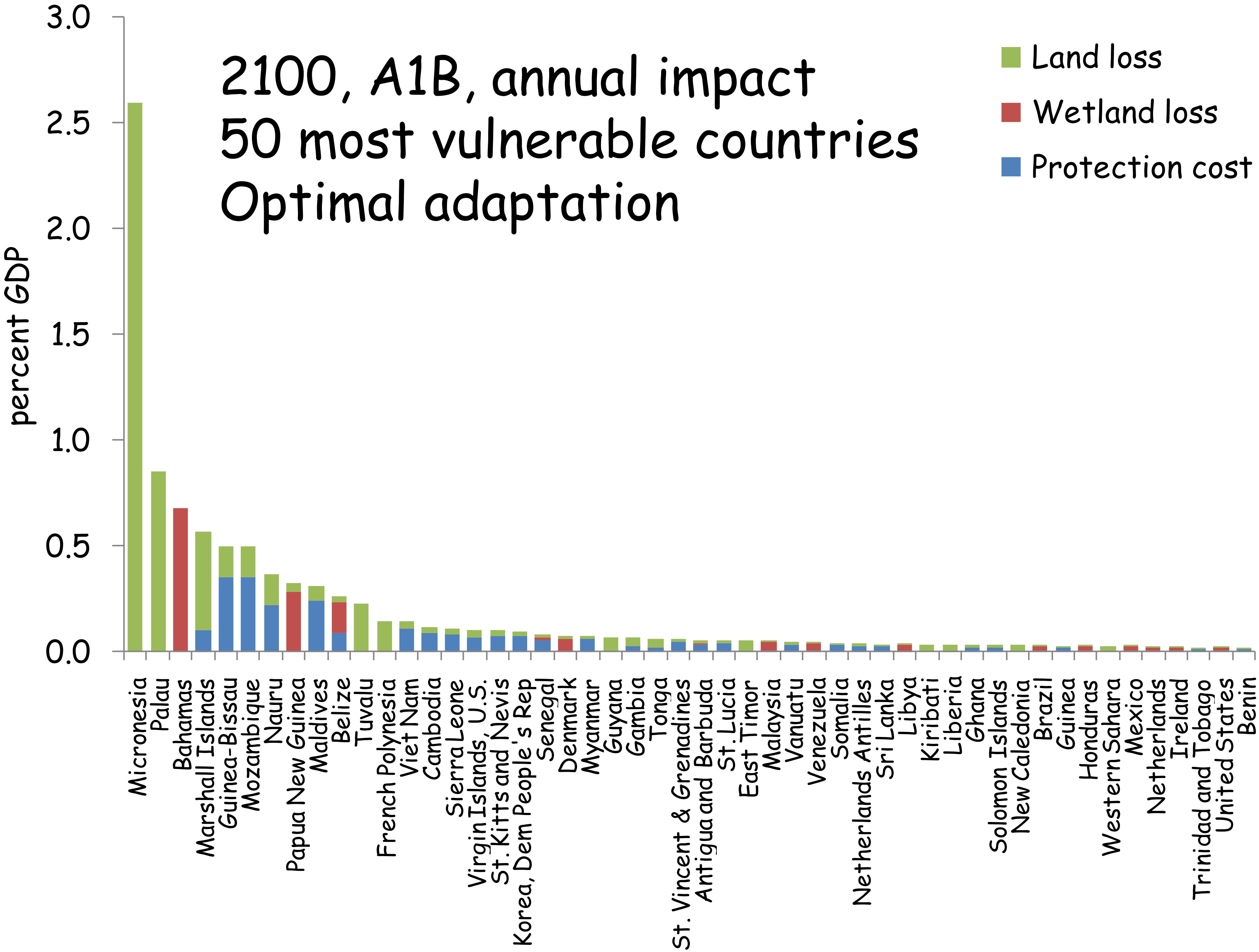
Brander, Florax, Vermaat, 2006, Ecological Economics

Gruenspecht's Law

One cannot study impacts without studying adaptation



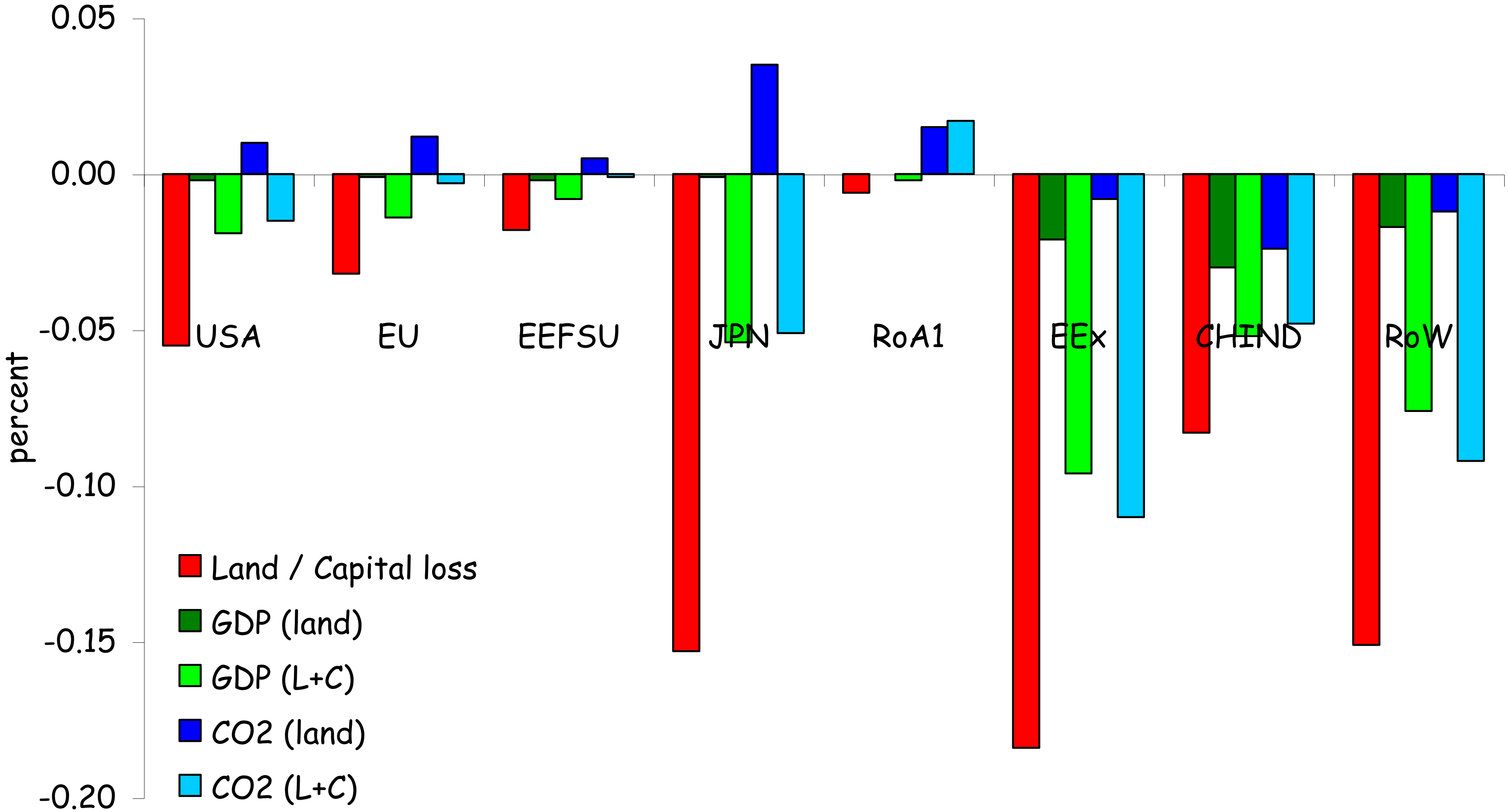
Observed adaptation
100
10
1
0.1
0.01
0.001
10
100
1000
10000
100000
People affected by floods (1/000/yr)
Income ($/p/yr)


2100, A1B, annual impact
50 most vulnerable countries
Optimal adaptation
Land loss
Wetland loss
Protection cost
percent GDP
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Micronesia
Palau
Bahamas
Marshall Islands
Guinea-Bissau
Mozambique
Nauru
Papua New Guinea
Maldives
Belize
Tuvalu
French Polynesia
Viet Nam
Cambodia
Sierra Leone
Virgin Islands, U.S.
St. Kitts and Nevis
Korea, Dem People's Rep
Senegal
Denmark
Myanmar
Guyana
Gambia
Tonga
St. Vincent & Grenadines
Antigua and Barbuda
St. Lucia
East Timor
Malaysia
Vanuatu
Venezuela
Somalia
Netherlands Antilles
Sri Lanka
Libya
Kiribati
Liberia
Ghana
Solomon Islands
New Caledonia
Brazil
Guinea
Honduras
Western Sahara
Mexico
Netherlands
Ireland
Trinidad and Tobago
United States
Benin

General equilibrium effects

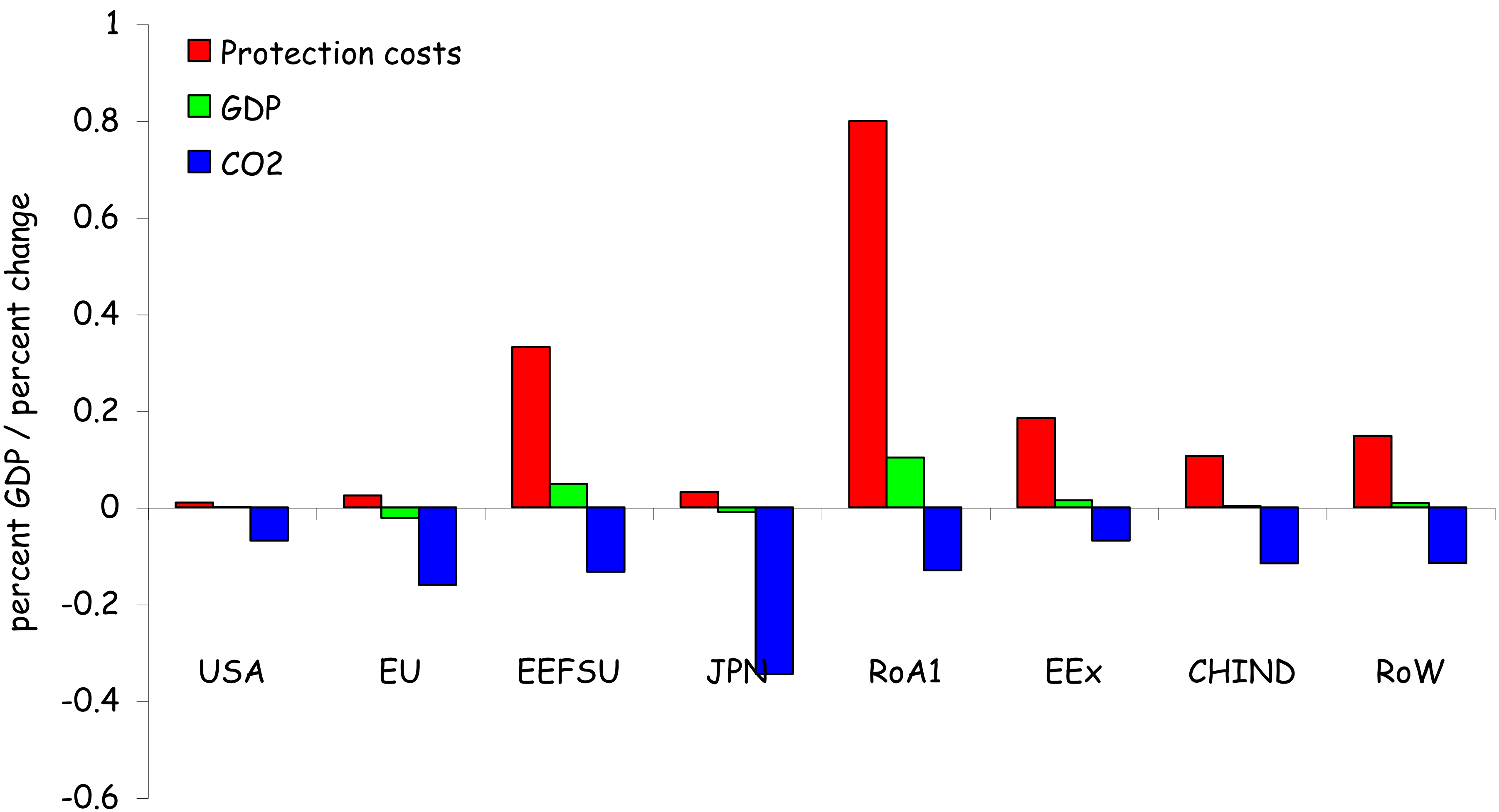
- What are the wider economic implications?
- Land loss would affect agriculture, and hence all other markets
- Coastal protection would affect construction and capital
- Static CGE model
- Dryland lost is a loss of the endowment land; we also include a case in which a proportional amount of capital is lost
- Coastal protection is a defensive investment, financed by a forced increase in savings

No protection; 2050; 25 cm SLR

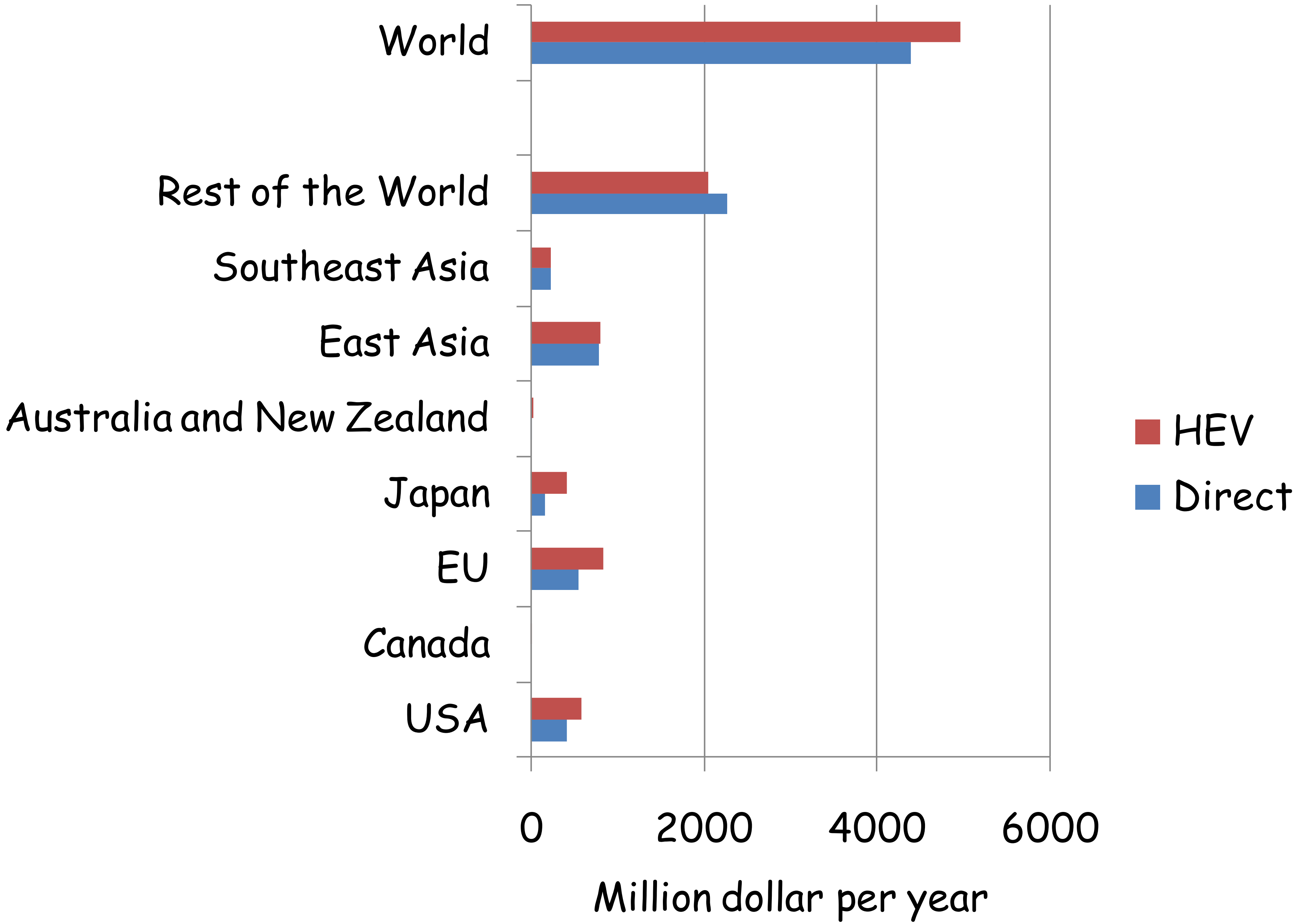


Bosello, Roson, Tol, 2007, Environmental and Resource Economics

Full protection; 2050; 25 cm SLR



Bosello, Roson, Tol, 2007, Environmental and Resource Economics



Darwin, Tol, 2001, Environmental and Resource Economics

Conclusions

- Sea level rise is one of the better understood impacts
- Estimates are uncertain, however, partly because the current data are not very good, and partly because the impact is in a remote future
- Two big uncertainties are wetland value and adaptation
- Unknowns include saltwater instrusion and storms

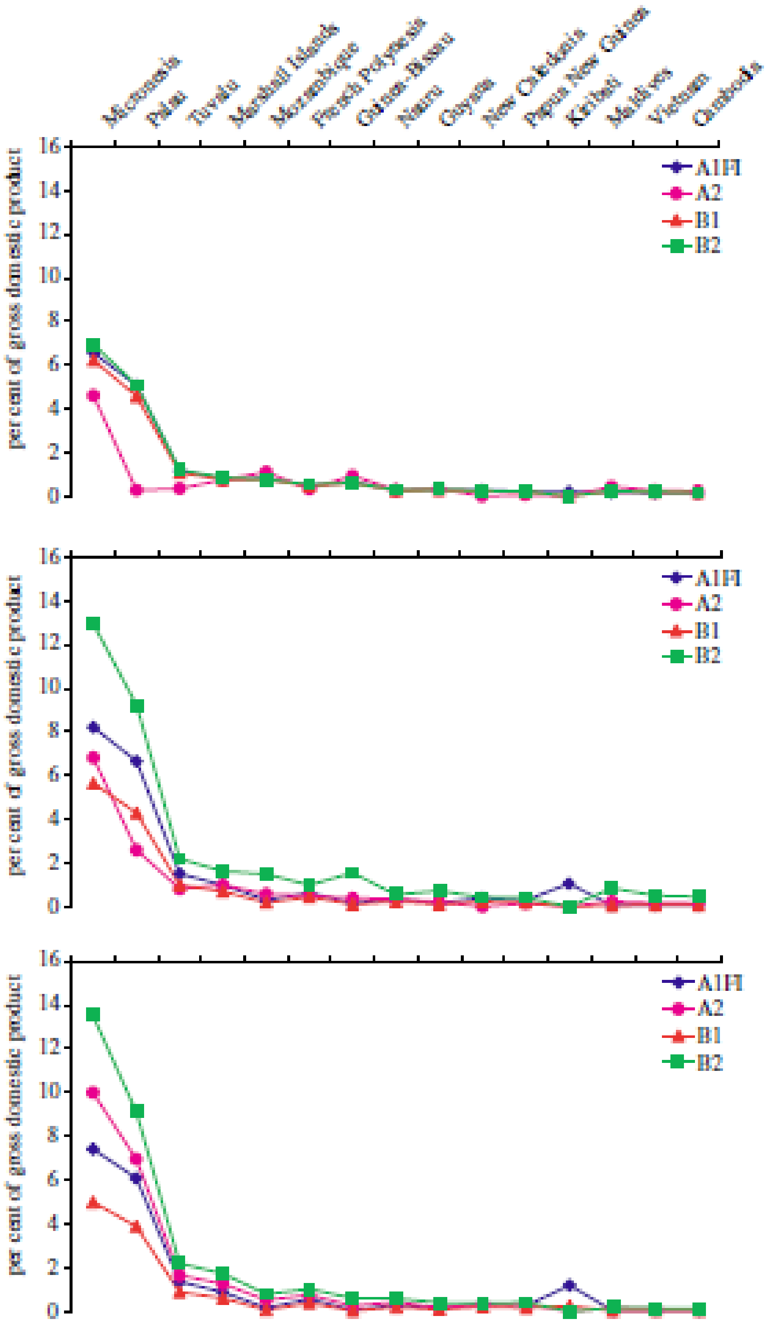
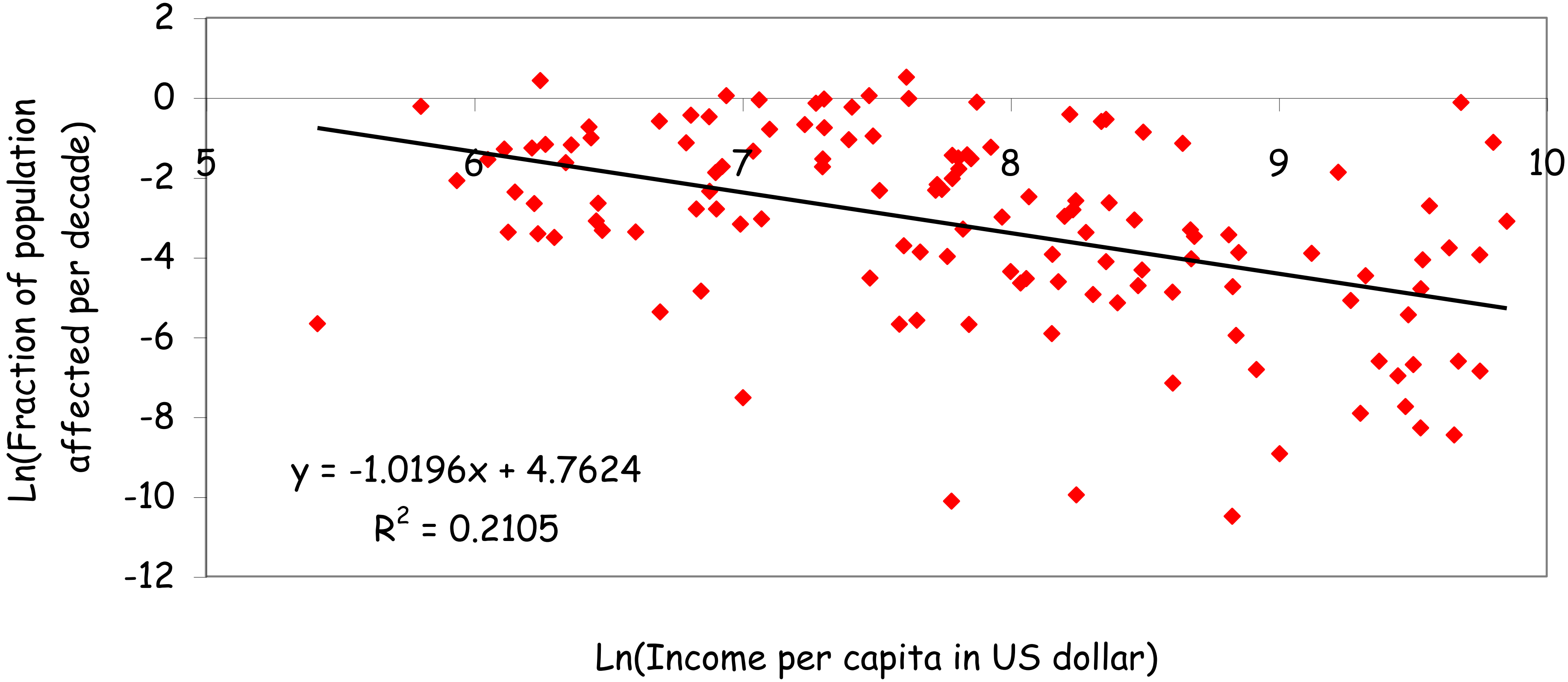


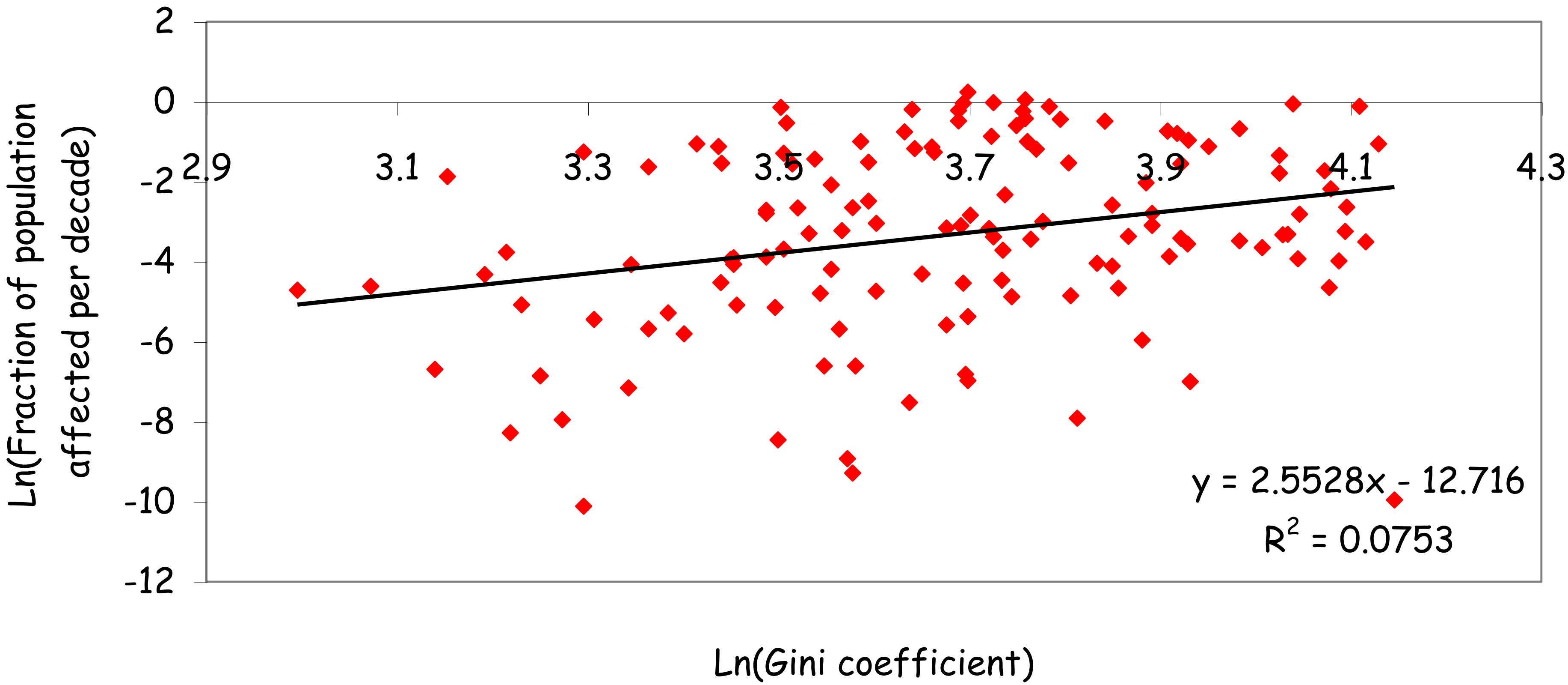
Figure 10. Protection costs as a percentage of current gross domestic product for the 15 most affected countries under the four SRES worlds (A1FI, A2, B1, B2): 2020s (*a*), 2050s (*b*) and 2080s (*c*).

Vulnerability to Natural Disasters and Per Capita Income

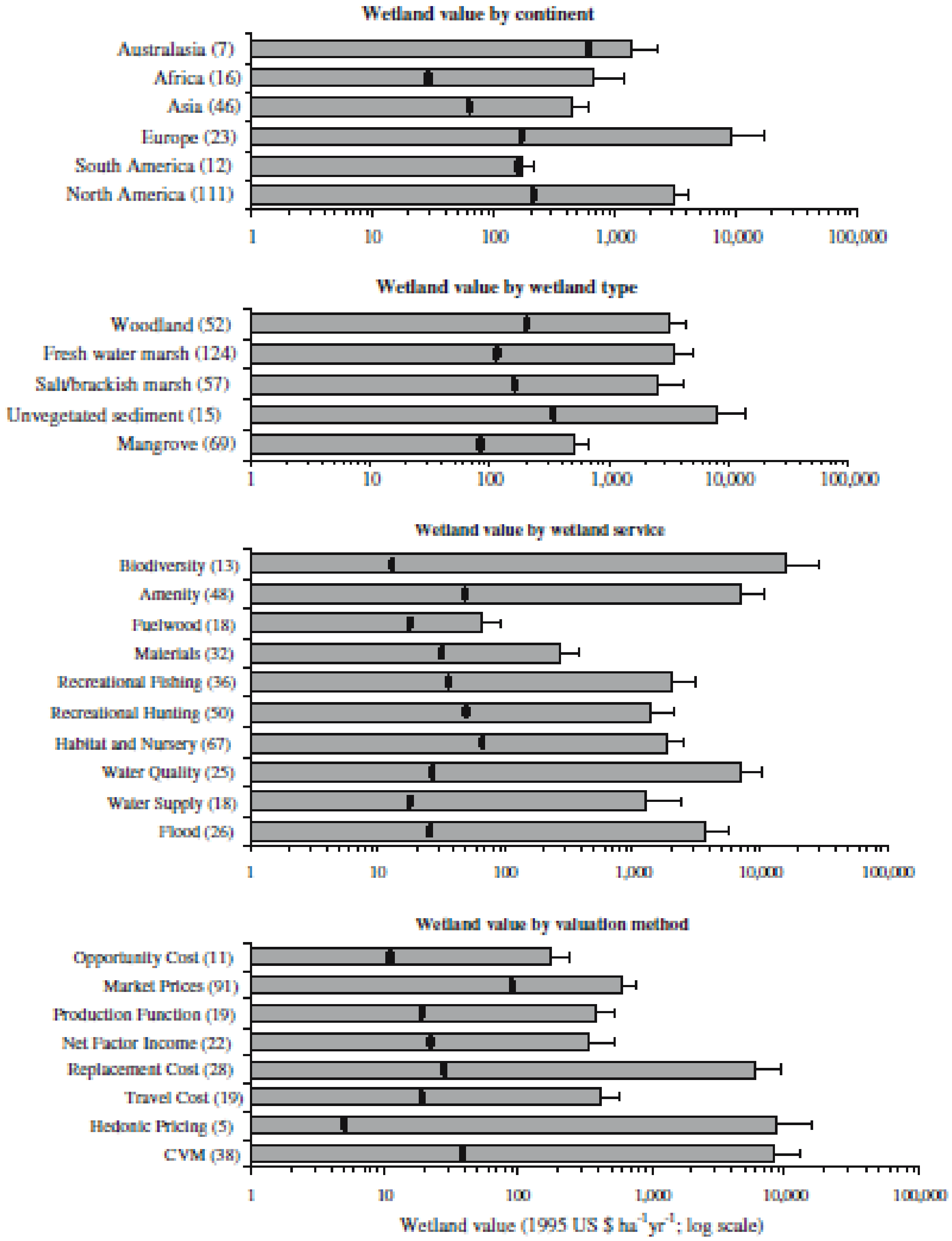


Yohe and Tol, 2002, GEC

Vulnerability to Natural Disasters and Income Distribution



Yohe and Tol, 2002, GEC



Wetland value by continent
Australasia (7)
Africa (16)
Asia (46)
Europe (23)
South America (12)
North America (111)
1
10
100
1,000
10,000
100,000
Wetland value by wetland type
Woodland (52)
Fresh water marsh (124)
Salt/brackish marsh (57)
Unvegetated sediment (15)
Mangrove (69)
1
10
100
1,000
10,000
100,000
Wetland value by wetland service
Biodiversity (13)
Amenity (48)
Fuelwood (18)
Materials (32)
Recreational Fishing (36)
Recreational Hunting (50)
Habitat and Nursery (67)
Water Quality (25)
Water Supply (18)
Flood (26)
1
10
100
1,000
10,000
100,000
Wetland value by valuation method
Opportunity Cost (11)
Market Prices (91)
Production Function (19)
Net Factor Income (22)
Replacement Cost (28)
Travel Cost (19)
Hedonic Pricing (5)
CVM (38)
1
10
100
1,000
10,000
100,000
Wetland value (1995 US $ ha-1 yr-1; log scale)

Modeling changes in ocean biogoechemistry due to climate change and ocean acidification

Sarah Cooley (WHOI; scooley@whoi.edu)

December 31, 2010

As rising anthropogenic carbon dioxide emissions have contributed to climate change by altering the Earth's radiative balance, about one-third of this carbon dioxide (Sabine et al. 2004; Intergovernmental Panel on Climate Change 2007) has also dissolved in the ocean to cause ocean acidification (OA), a much less well-publicized phenomenon. The physical chemistry of OA is very well understood, and these changes have been observed at many locations worldwide. Observational data have contributed to the development and testing of coupled ocean models used to examine climate change and ocean acidification. However, we do not have enough information yet to predict the biological responses to ocean acidification for more than a handful of organisms. As a result, forecasts of the ecological responses to ocean acidification still contain great uncertainty. Predicting OA's socioeconomic effects is also therefore in its infancy. Determining the end-to-end effects of ocean acidification will require a combination of data collection and synthesis, model and method development in multiple disciplines, and intercomparison and linking of earth system, ecological, and socioeconomic models.

CHEMISTRY & OBSERVATIONS

Ocean acidification refers to the suite of chemical changes that occur when excess atmospheric carbon dioxide (CO_2) from human activities reacts with water molecules to form carbonic acid, a weak acid that partially dissociates into hydrogen ions and bicarbonate. Some of the carbon dioxide molecules also react with dissolved carbonate ions that are already present, forming more bicarbonate. The net chemical consequences of these reactions are an increase in hydrogen ions, a decrease in carbonate ions, and an overall increase in the content of dissolved CO_2 species in water. The increase in hydrogen ions increases solution acidity, which also decreases measured pH.

The total quantity of dissolved CO_2 and carbonate system species in seawater, or the inorganic carbon system, can be measured directly or calculated from other observed parameters. Any two of the four parameters including total dissolved inorganic carbon (DIC; the total amount of dissolved CO_2, bicarbonate, and carbonate ions), total alkalinity (TA; the excess base in seawater), pH, and the partial pressure of CO_2 (pCO_2), can be derived from two other measured parameters. Other difficult-to-measure parameters, such as the concentration of carbonate ions and the saturation state of calcium carbonate minerals (Ω), can also be derived similarly. When state-of-the-art methods, standards, and tightly controlled laboratory conditions are used, measured DIC, TA, pH, and pCO_2 have uncertainties ranging from ~0.03%~0.2% (depending on parameter; Dickson, 2009, personal communication). Uncertainties double if analyses are done in less tightly controlled conditions (e.g., at sea). Historically, observational campaigns have usually measured seawater DIC and TA, then calculated pH and pCO_2. Using this method, measurement uncertainties plus error in equilibrium constants yield a combined resultant error of 0.6%-6.3% in derived parameters (Dickson and Riley 1978). The carbonate ion concentration derived by this method has an error of 3.1%; hydrogen ion concentration has an error of 5.6% (Dickson and Riley 1978). Consequently, uncertainty around values of Ω calculated from derived carbonate ion concentrations are of a similar magnitude as the annual rate of change in Ω (-0.09 $year^{-1}$) observed at time-series stations like ALOHA (Figure 1 in Feely et al. 2009a), which underscores the necessity of long-term ocean acidification monitoring with high-quality measurements.

Seawater chemistry measurements from time-series stations and repeat hydrography cruises show the global extent and progress of ocean acidification. The inorganic carbon chemistry of upper-ocean seawater has been tracked at monthly monitoring locations including ALOHA near Hawaii, BATS near Bermuda, station PAPA in the North Pacific, and ESTOC near the Canary Islands, and records show a progressive decrease in upper-ocean pH, Ω, and/or carbonate ion concentration as seawater CO_2 rises (Dore et al., 2009, updated in Doney 2010; Gruber et al. 2002; González-Dávila et al. 2010). Comparison of datasets from repeat hydrography programs has shown that changes in ocean carbonate chemistry due to the invasion of anthropogenic CO_2 penetrate thousands of meters in each ocean basin (Sabine et al.

2004). Variabilities of pH and pCO_2 are naturally greater in coastal regions because of respiration, photosynthesis, and runoff, so ocean acidification research must also determine what conditions may be damaging there (National Research Council 2010). Numerous programs now focus on establishing baseline conditions in many more locations, such as the Arctic Ocean (Azetsu-Scott et al. 2010; Cai et al. 2010), but infrastructure development is still required to collect enough data to determine baseline conditions and indicate future changes in all regions (Feely et al. 2009b).

Ocean acidification and climate change are also expected to alter other nutrient cycles. Decreases in pH and carbonate ions will affect the solubility, adsorption, toxicity, and rates of redox reactions for metals in seawater (Millero et al. 2009). The biological availability of many metals could change, with varying outcomes: increased copper could kill more phytoplankton, whereas increased iron could support more phytoplankton growth. These changes could be especially important in estuarine biogeochemical cycling, where redox reactions tightly control the behavior of metals and gaseous components like CO_2, which in turn control phytoplankton community composition (Millero et al. 2009). Throughout the oceans, ocean acidification and climate change may also alter nitrogen cycling. Bacterial nitrification could slow as pH decreases and cyanobacterial nitrogen fixation could increase as temperature and CO_2 levels rise, promoting an overall shift towards a larger reduced nitrogen pool dominated by ammonia (Hutchins et al. 2009). At the same time, increasing temperature could slow vertical mixing and thereby reduce upwelling of nutrients from deep water, enhancing nutrient limitation. These consequences of ocean acidification are somewhat less well quantified than the expected changes in pH and carbonate ion concentration, so present OA forecasts primarily focus on inorganic carbon cycle-related changes in the oceans.

EARTH SYSTEM MODELS

Coupled ocean models used to study climate change often include carbon cycles that interact with meteorological variables, oceanographic variables, and biogeochemical processes; therefore, these models simulate ocean acidification as well as other anthropogenically forced changes in Earth systems. Model-data comparisons are used to judge the models' skill at creating hindcasts, and the models that reproduce major features of circulation and tracer transport are believed to provide credible estimates of future climate change at large scales (Intergovernmental Panel on Climate Change 2007). Intercomparison exercises, such as the international Ocean Carbon Model Intercomparison Project (OCMIP), then compare forecasts from multiple skillful models to develop estimates of the range of future conditions. Atmospheric CO_2 levels of ~780 ppm by 2100 (IS92A scenario, Leggett et al. 1992) yielded a median response for OCMIP's thirteen models in which ocean pH decreased by 0.3-0.4 and carbonate ion concentrations dropped globally. Overall, there will be an equatorward contraction and shallowing of high-carbonate waters suitable for animals that make hard shells and skeletons (Orr et al. 2005). Meanwhile, temperature increases due to climate change that decrease CO_2 solubility will counteract less than 10% of the chemical changes associated with ocean acidification (Orr et al. 2005). The subsequent Coupled Climate-Carbon Cycle Intercomparison Project (C4MIP) found that in 11 climate models with land and ocean carbon cycles, feedbacks between climate change and the carbon cycle would occur and increase atmospheric CO2 by an additional ~50-100 ppm, causing additional warming and allied changes (Intergovernmental Panel on Climate Change 2007).

The biogeochemical consequences of future ocean carbon cycle changes are less clear at present. Intercomparison has shown that accurate physics are a very strong determinant of whether modeled biogeochemical processes replicate observed conditions (Doney et al. 2004; Najjar et al. 2007). Detailed intercomparisons of biogeochemical parameterizations in coupled models, though, are often limited for several reasons. First, the level of biogeochemical complexity in the OCMIP/C4MIP models varies greatly, and appropriate evaluation methods and criteria for each model depend on their specific biogeochemical parameterizations. Second, spatially or temporally sufficient data is often lacking for evaluating many modeled biogeochemical processes in detail. Third, modeled biogeochemical parameters (e.g., growth of a generalized pool of zooplankton) are often not directly comparable to observational data (Doney et al. 2009). Most biogeochemical models do undergo qualitative or quantitative model-data comparison (68%), but there is no standardized approach, and few assessments use in-depth statistical techniques for model-data comparison (Stow et al. 2009). Some models involved in OCMIP and subsequent intercomparison studies have undergone extensive model-data comparison individually. For example, Community Climate System Model (CCSM3) output was evaluated using satellite-derived surface ocean chlorophyll and primary productivity, climatologies of nutrients and pCO_2, and time-series data from observational programs like JGOFS (Doney et al. 2009). This model had the strongest model-data correlations for SST and nutrients, moderate correlations for surface pCO_2 and CO_2 air-sea flux, and weaker correlations for ecosystem variables including chlorophyll, primary production, phytoplankton growth rate, etc. (Doney et al. 2009). Further improvements to the biogeochemical model and its feedbacks may bring the ecosystem variables, which are the most dependent on its parameterizations, into better agreement with observations. To that end, a new model that builds upon CCSM, called the Community Earth System Model (CESM), is being developed and tested (University Corporation for Atmospheric Research 2010). Similar work is underway with other coupled models.

The primary uncertainty in ocean acidification chemistry forecasts comes not from the carbon chemistry itself, measurements, or from coupled models' abilities to predict ocean carbon inventories, but rather from the uncertainty in anthropogenic CO_2 emission trajectories (Intergovernmental Panel on Climate Change 2007). The rate of change of ocean acidification in offshore seawater appears to mirror the rate of atmospheric CO_2 rise (Figure 1 in Feely et al. 2009a). Even if the atmospheric CO_2 trajectory levels off today, ocean pH, surface Ω, and deep-ocean Ω will continue to be depressed compared to preindustrial conditions in the next five centuries (Frölicher and Joos 2010). Long-term forecasts suggest that oceanic uptake of CO_2 will slow as the chemical changes from OA accumulate (Sabine and Tanhua 2010) and as ocean circulation slows from climate change (Intergovernmental Panel on Climate Change 2007), but these factors will not reverse ocean acidification either. Over shorter periods, a moderate amount of uncertainty about ocean acidification's progress in coastal zones is associated with the possibility of changes in freshwater cycling and deposition of other, acid-generating pollutants near shore (Doney et al. 2007; Doney 2010).

Biological responses & models

Most of the uncertainty about OA's effects on marine ecosystems arises from our present incomplete knowledge about the individual and population-level responses to OA. Any of the chemical changes due to ocean acidification may be biologically relevant (reviewed in National Research Council 2010). The decline in carbonate ions decreases the amount of carbonate building blocks available for marine animals that create calcium carbonate shells and skeletons. These organisms include primary producers such as coccolithophores and coralline algae, zooplankton such as pteropods, mollusks such as clams, oysters, and mussels, crustaceans such as crabs and lobsters, and reef-forming corals. Most of the calcifying organisms studied show negative responses to ocean acidification such as decreasing calcification rates, delayed larval development, and smaller shells (Kroeker et al. 2010). The cellular and organismal mechanisms behind these responses are not yet clear. In other organisms, the decrease in seawater pH, the increase in CO_2, or both may affect concentration gradients of hydrogen ions across cell membranes or change oxygen-CO_2 respiratory balances (National Research Council 2010). Finally, increasing CO_2 concentrations from ocean acidification may benefit photosynthetic organisms like phytoplankton, macroalgae, and seagrasses.

Scaling ocean acidification's effects on individual organisms to populations and ecosystems remains a challenge. Not only will OA's effects on individuals alter their individual performance, but it may also alter their behavior in ways that will generate population-wide consequences. For example, ecosystem-scale observations in natural environments have reported declines in calcifier populations and increases in seagrass populations with increased proximity to CO_2 vents (Hall-Spencer et al. 2008), and shifts from calcifier-dominated communities to photosynthesizer- and invertebrate-dominated communities with long-term pH decreases (Wootton et al. 2008). Until ocean acidification's effects on both life functions and behaviors of susceptible species are known, modeling studies are limited to using statistical responses generalized from individual studies and falling within trends observed in ecosystem-based studies such as these.

In the absence of mechanistic knowledge of marine organisms' responses to OA, applying statistical relationships describing general responses can still be instructive for providing first estimates of OA's total impacts. Brander et al. (2009) estimated the economic impacts of OA on coral reefs by relating loss of coral cover to ocean acidification using a general relationship summarizing multiple coral studies and an economic value meta-analysis. They concluded that losses were approximately one order of magnitude smaller than those from climate change. However, only broad insight is available from this study because the analysis depends heavily on an assumed linear biological response (loss of coral cover) that may in nature be nonlinear, stepped, or otherwise episodic (Kleypas and Yates 2009). In another analysis, Cooley and Doney (2009) determined the potential losses from ocean acidification to United States commercial mollusk harvests by assuming that calcification rate decreases in mollusks directly correlated to population decreases. They concluded that annual losses in ex-vessel revenue could range from the tens to hundreds of millions of dollars. Their linear damage function approximated trends comparable to those in individual and ecosystem studies, but it did not explicitly include interspecies interactions, adaptability, or long-lasting damage to juveniles, all of which could affect populations over time periods relevant to the analysis. Until more biological data is available, initial studies like these must necessarily use statistical fits instead of mechanistic responses, but these types of studies must be interpreted with care to avoid drawing conclusions broader than the ingoing biological information permits.

CONCLUSIONS & FUTURE WORK

The chemical reactions and equilibria governing carbon dioxide's behavior in seawater have been well understood for decades to centuries, and worldwide observational datasets (e.g., Figure 1 in Feely et al. 2009a) that show decreasing ocean pH and carbonate ion concentration with rising atmospheric CO_2 levels agree with scientific theory. Ocean acidfication's effects on ocean chemistry can be forecast when this well-understood physical chemistry is included in the ocean carbon cycle of coupled ocean models. Intercomparisons of multiple skillful models suggest that ocean acidification will progress globally, and its progression depends greatly on atmospheric CO_2 emissions trajectories. CO_2 emissions, however, depend fundamentally on human behavior, which is far more uncertain. Local factors and climate change will exert secondary control on OA in nearshore regions.

Our ability to forecast ocean acidification's total effects on ecosystems and human economies under different CO_2 emissions scenarios is limited because our knowledge about biological responses to OA is incomplete. We also do not know how ocean acidification will affect coastal ecosystems where marine organisms thrive, although CO_2 concentration and pH variabilities there are already high. We do not know whether ecosystems will undergo stepwise responses or cross tipping points, and we do not understand how best to scale individual effects to population-wide responses.

Until some of these chemical and biological questions are resolved, we will be limited to making broad assessments of potential socioeconomic losses from ocean acidification using observed biological trends. Until then, modeling work must continue to ensure that biogeochemical model skill continues to improve. At the same time, ecosystem models of marine communities like EcoPath and Atlantis must be built, tested, and tuned to permit the extrapolation of biological responses to OA to ecosystems. Finally, socioeconomic studies must find improved ways to value the range of market and nonmarket services that marine ecosystems provide. These parallel efforts will permit skillful biogeochemical models to be linked to ecosystem models and to socioeconomic models.

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Modeling changes in ocean biogoechemistry due to ocean acidification and climate change

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January 28, 2011

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis

Sponsored by
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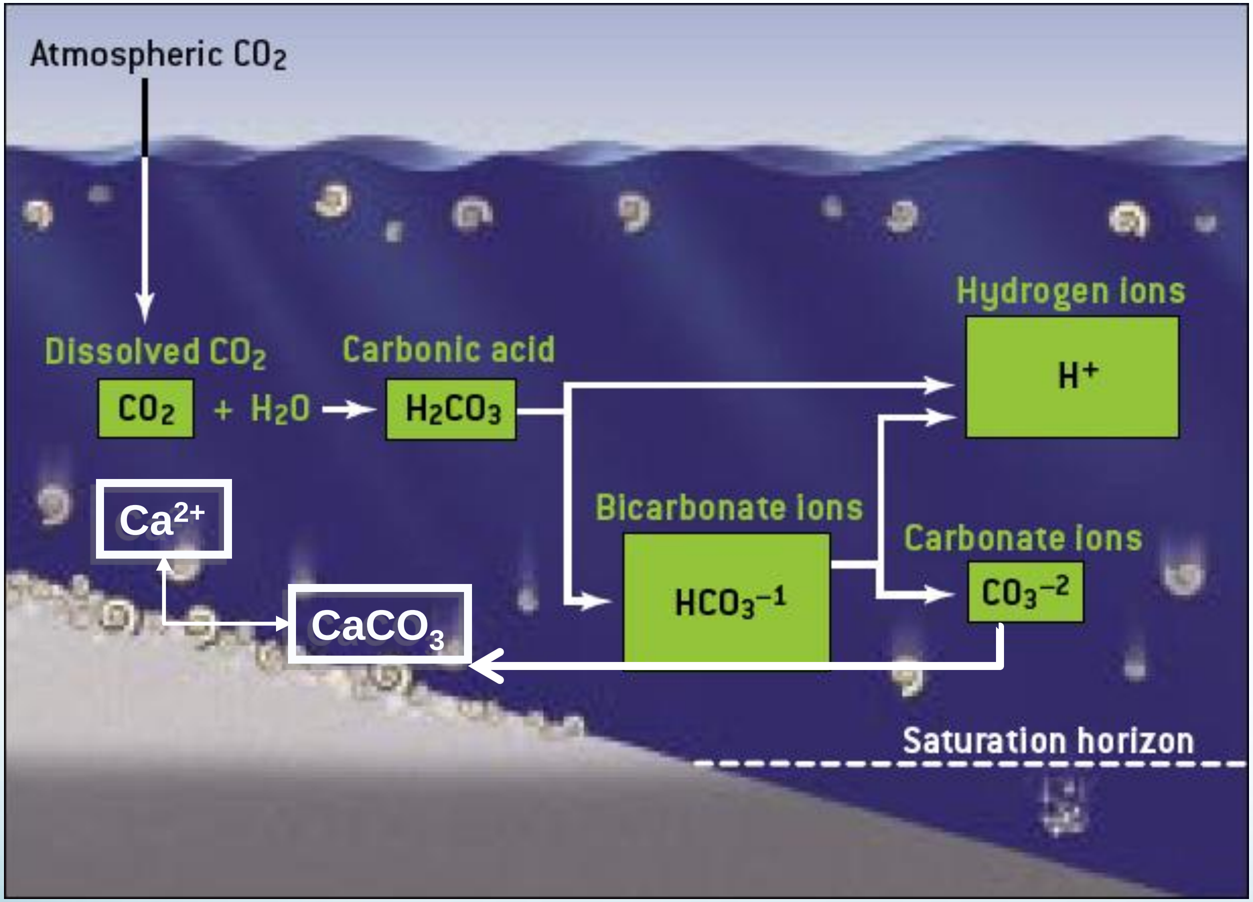
January 27-28, 2011
Capital Hilton, Washington, DC

Today's talk

- Chemistry & observations
  - What is OA? How well can we detect it?
- Earth system models
  - Ability to forecast future ocean conditions?
- Biological responses & models
  - How well can we forecast the future?
- Key knowledge gaps & needs

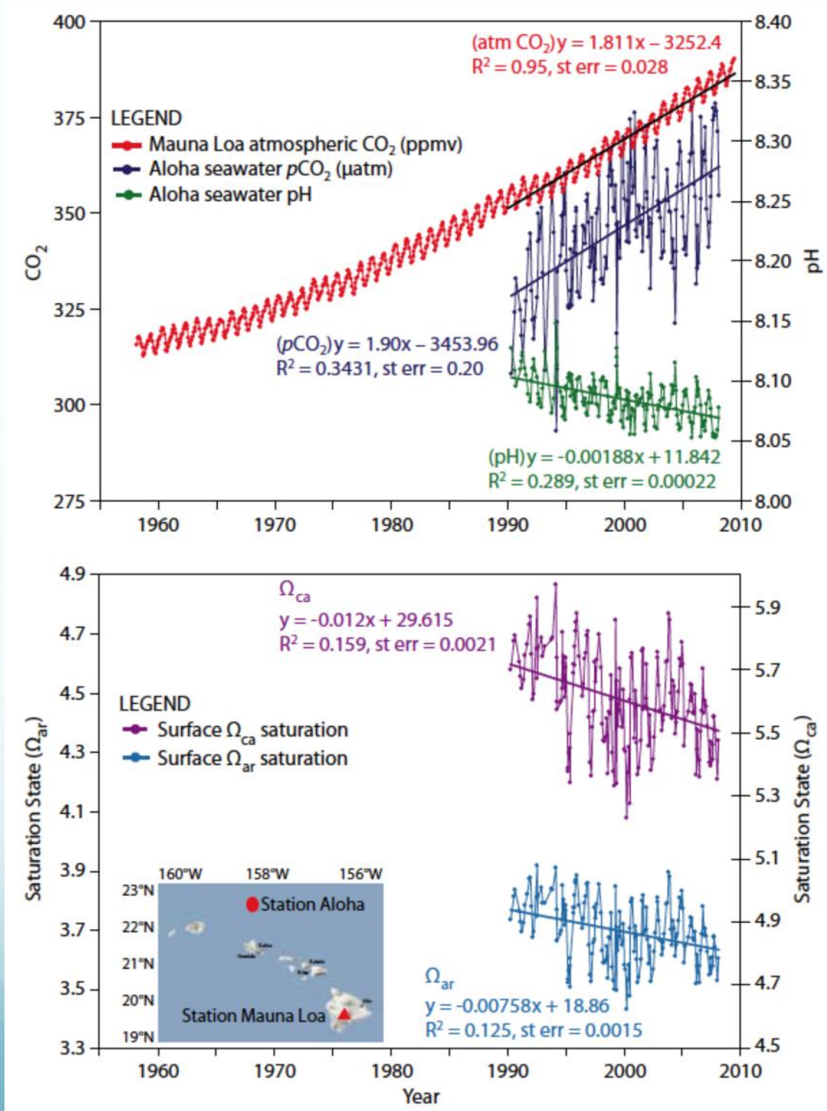
Rising CO_2 causes ocean acidification



Increasing CO_2
- Lowers pH
- Lowers $[CO_3^{2-}]$ saturation state "Ω"

Present change is faster than rock weathering & other compensatory mechanisms

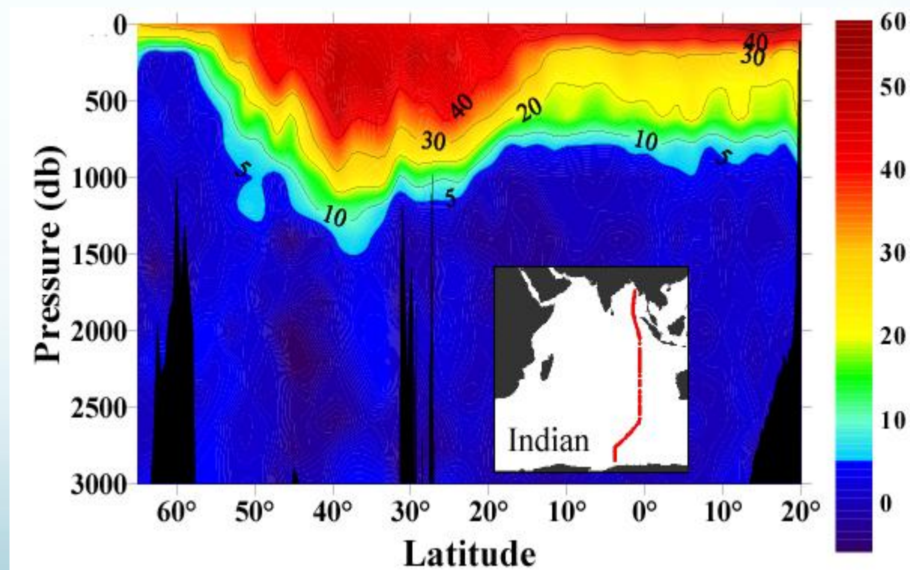
Observations show OA advancing



Now:

- ↑ Atmos. pCO_2
- ↑ Ocean pCO_2
- ↓ Ocean pH
- ↓ Calcite sat. st.
- ↓ Aragonite sat. st.
- ↑ Coastal variability

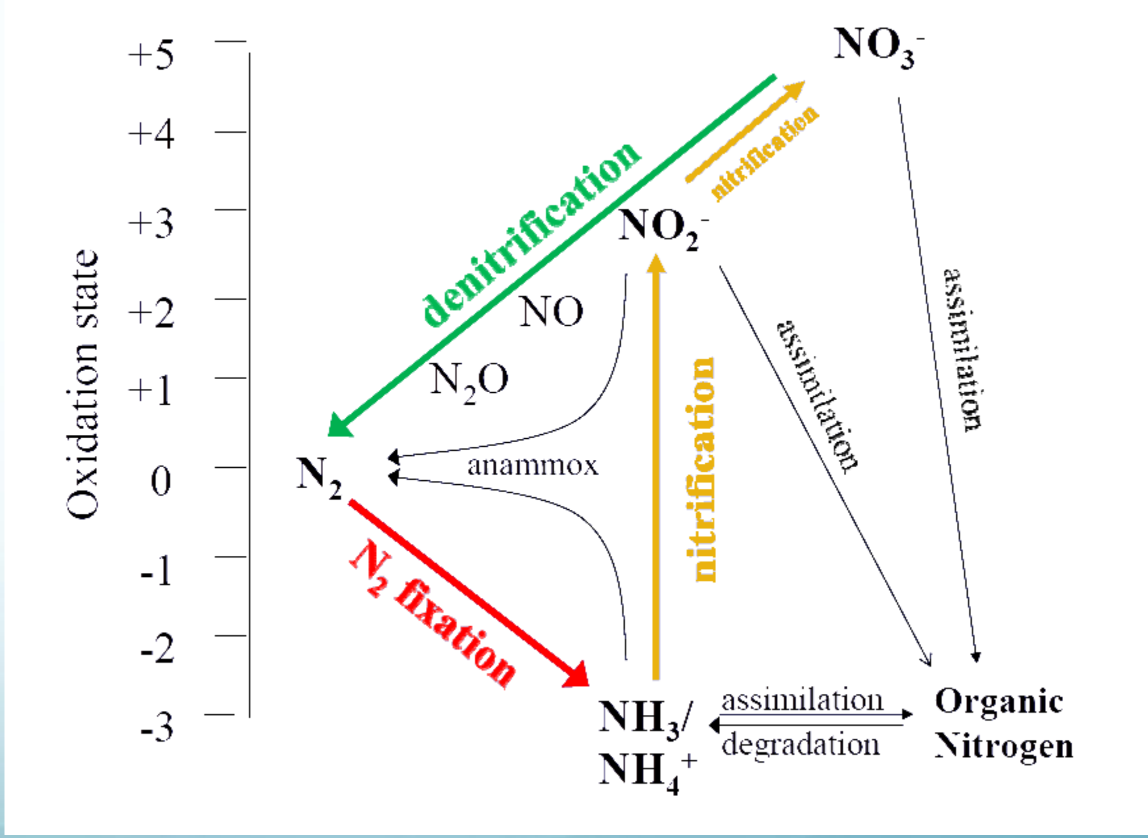
Anthropogenic CO_2 in upper ocean worldwide



Doney et al. *Oceanography* 2009, Sabine et al. *Science* 2004

Other effects & synergies

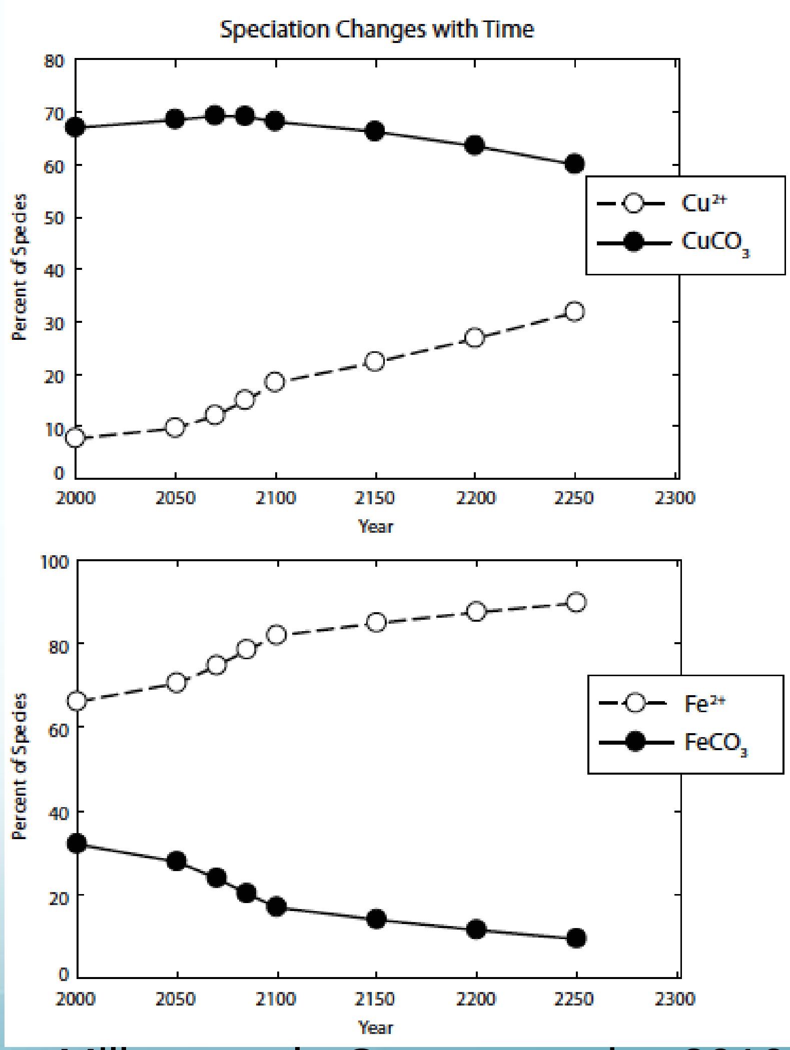
- Marine nitrogen pool shifts towards ammonia as N_2 fixers thrive in a high-CO_2 ocean



Hutchins et al., Oceanography, 2010

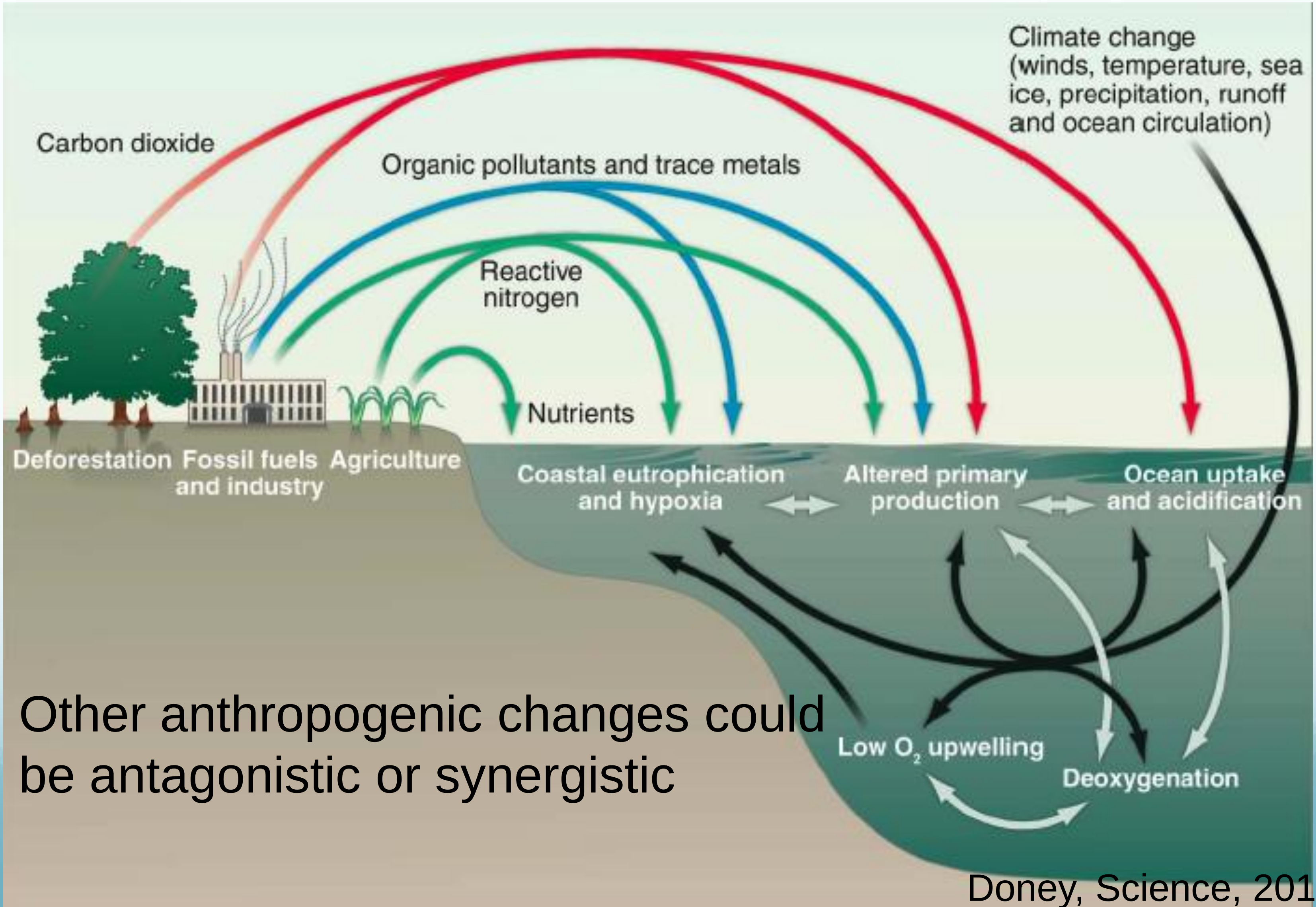
Other effects & synergies

- Metal ion speciation changes from changing pH and/or CO_2:
  - Copper (Cu^{2+}) increases: toxic!
  - Iron (Fe^{2+}) increases: fertilizer?



Millero et al., Oceanography, 2010

Other effects & synergies

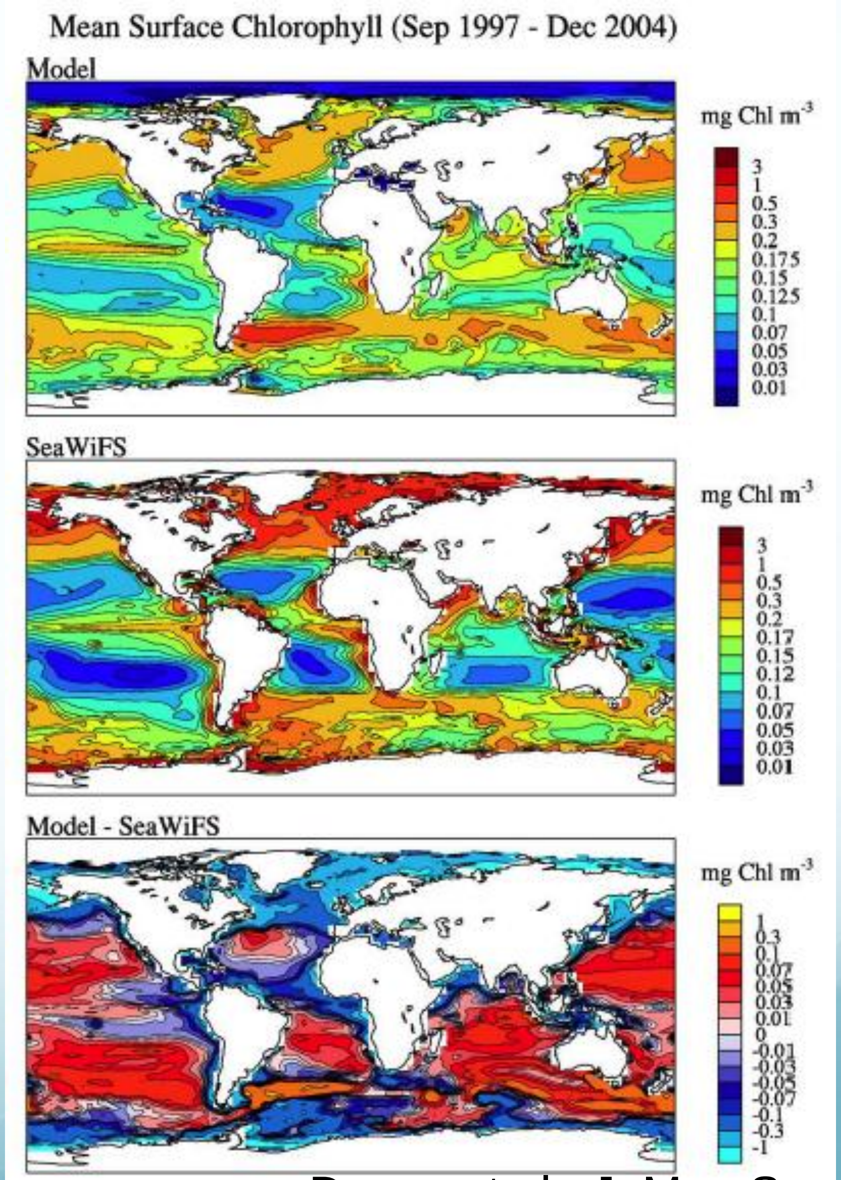


Other anthropogenic changes could be antagonistic or synergistic

Doney, Science, 2010

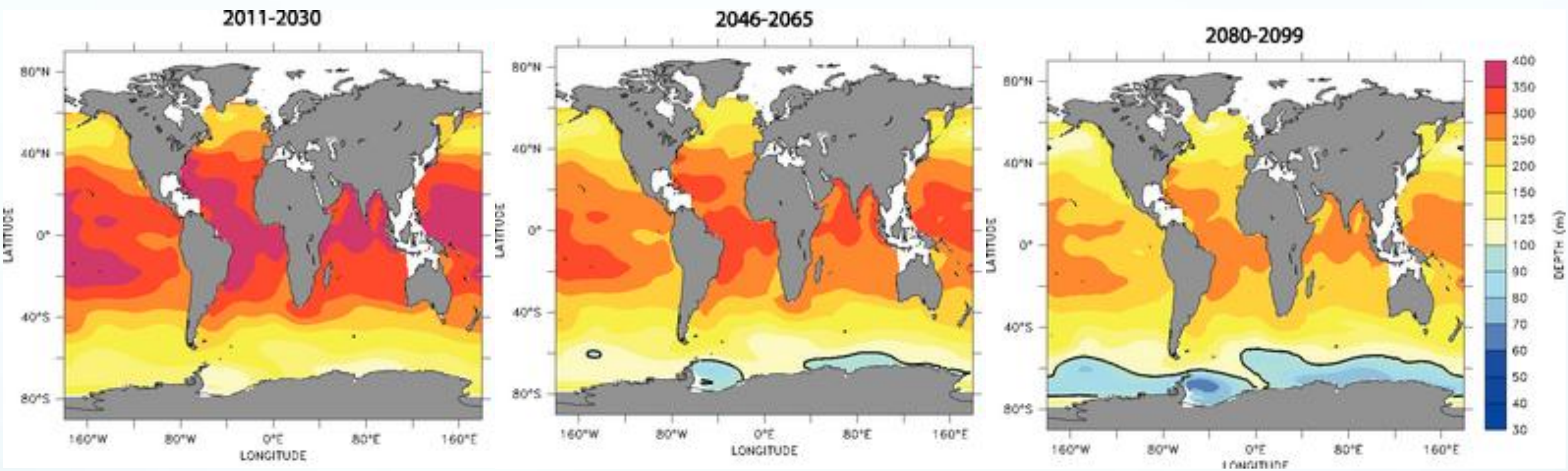
Earth system model simulations

- “Skill” evaluated with model-data comparisons of hindcasts
    - Simple & not-so-simple statistics
- Correct physics is key!
- BGC parameterizations are under continuous improvement



Doney et al., J. Mar. Sys., 20

Model intercomparison used to create, evaluate forecasts



Multi-model median of % saturation of carbonate ion from OCMIP-2 models: broad agreement that ocean pH and carbonate ion levels will decline in response to rising atmospheric CO2.

Key question: what will $CO_{2,atm}$ be?

IPCC, 2007

Biological Groups at Risk

Known

Warm-water corals

Cold-water corals

Some plankton

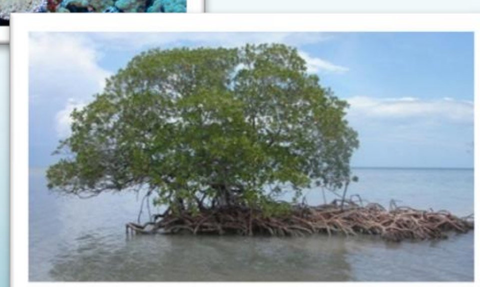
Pteropods

Many mollusks

Anticipated

Reef communities

Marine predators



Coastal environments

Fishermen

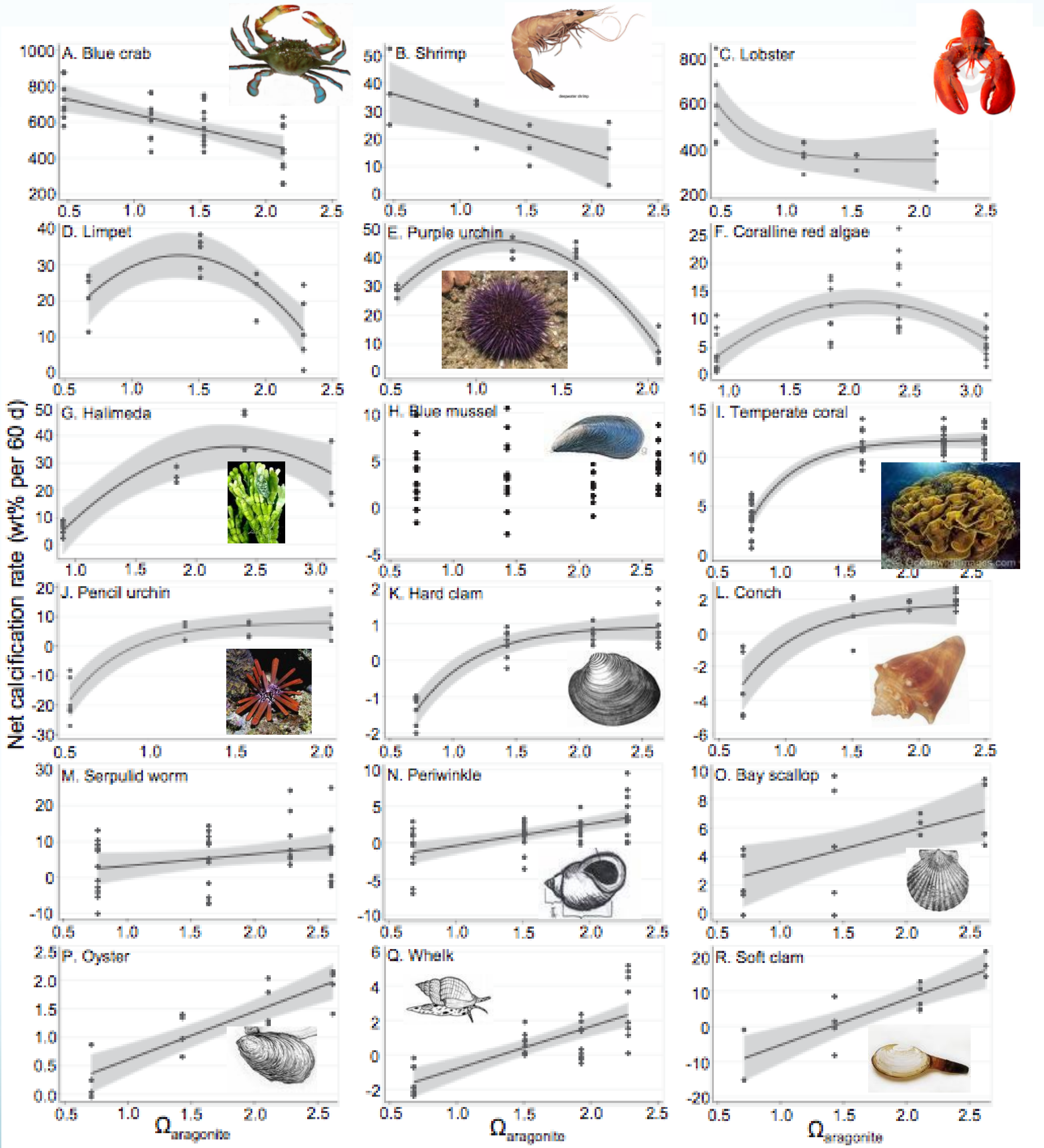
Businesses

Calcification responses vary

With decreasing Ω,

- Crustaceans ↑
- Urchins, some algae, corals ↶↷
- Mollusks ↓

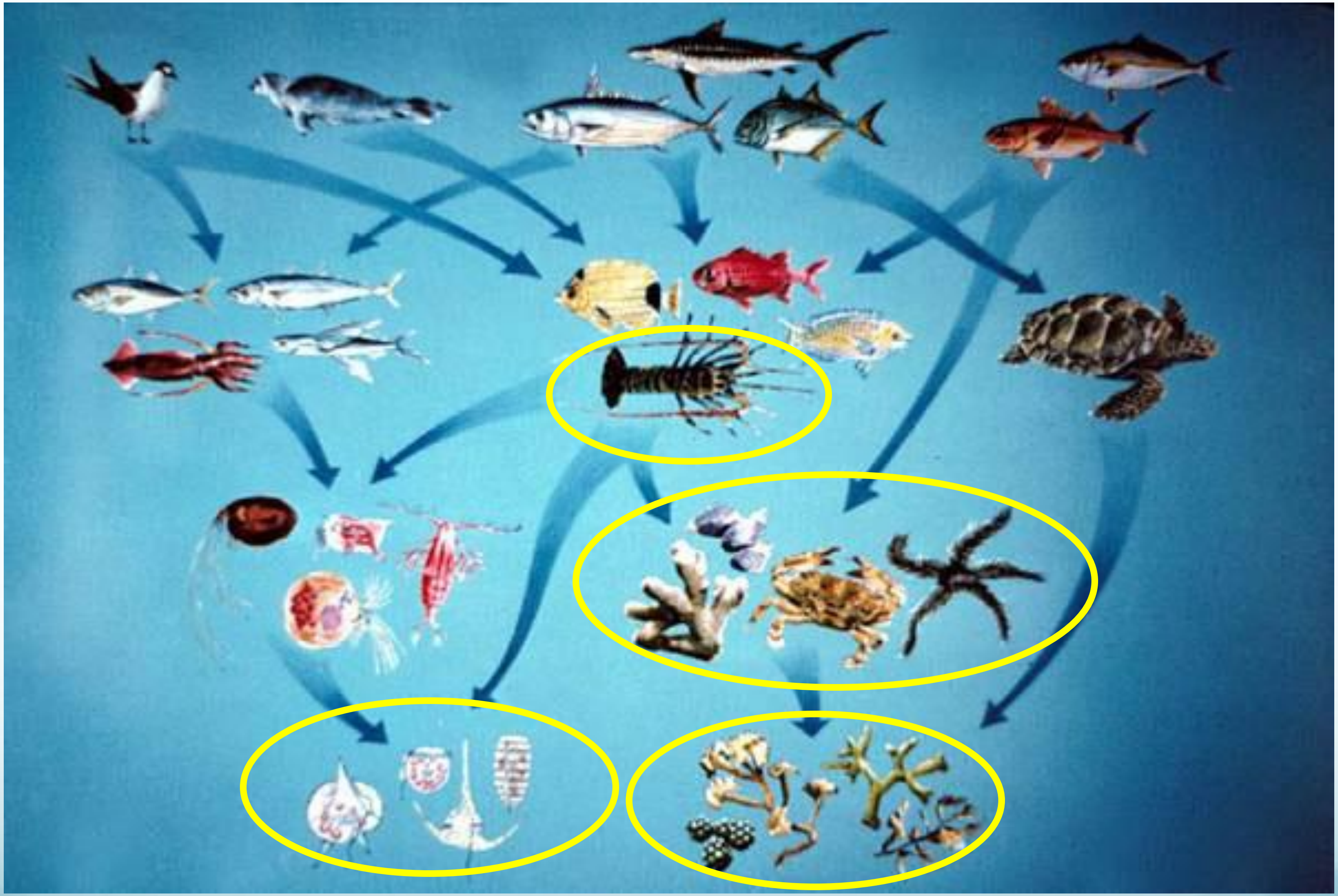
- **Individual & population implications not yet understood**



Saturation state

Ries et al., 2009, Geology

Ecological implications



Food web effects of OA are unknown, could be extensive

Ecosystem changes

In a coastal lagoon, noncalcifiers replaced many calcifiers over an 8-y. pH decline (8.41-7.99)

Photo, U. Washington

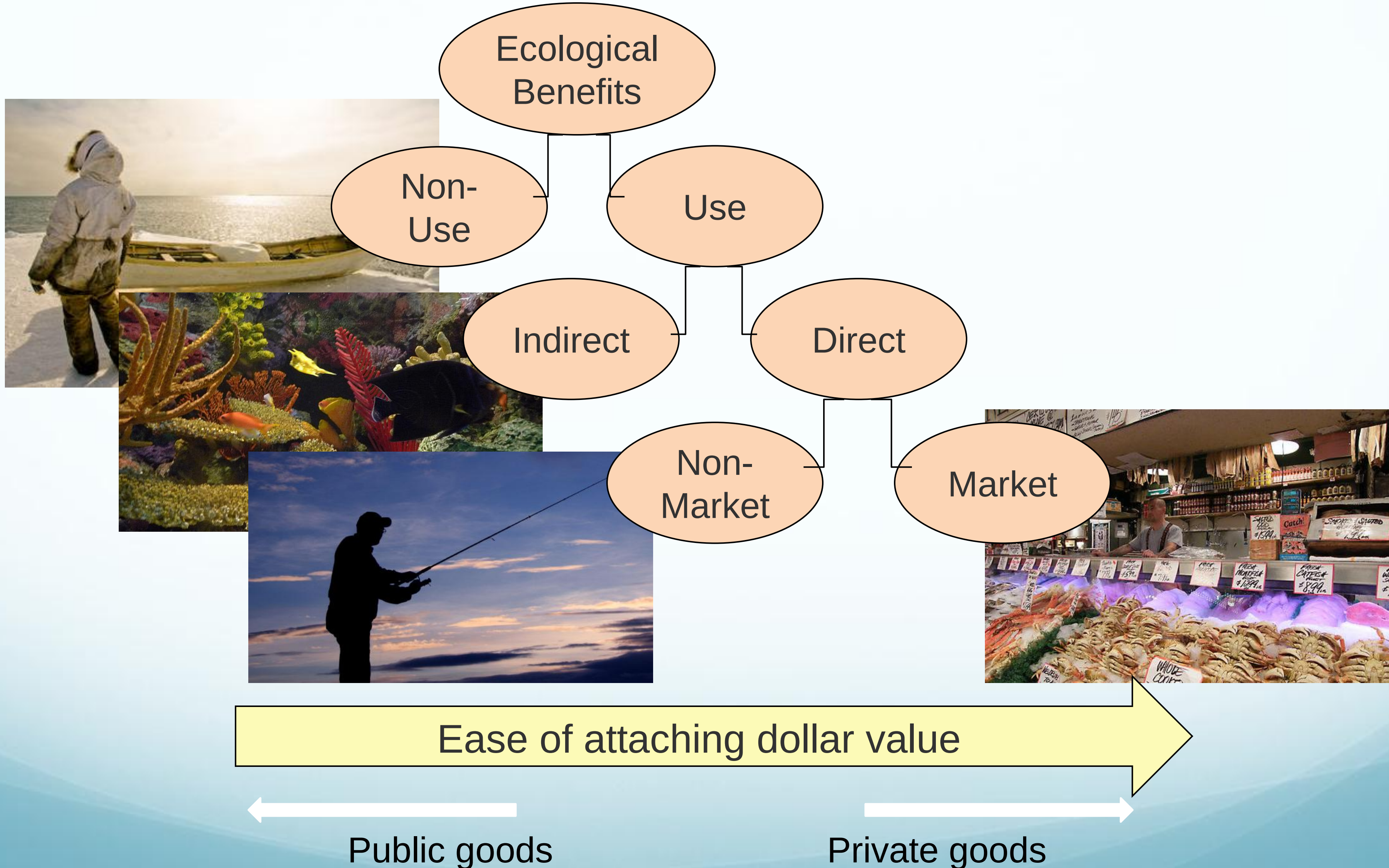
(Wootton et al. PNAS 2008)

Near a volcanic CO_2 vent,

- adult mollusks damaged
- juvenile mollusks absent
- corals, coralline algae absent

Hall-Spencer et al., Nature 2008

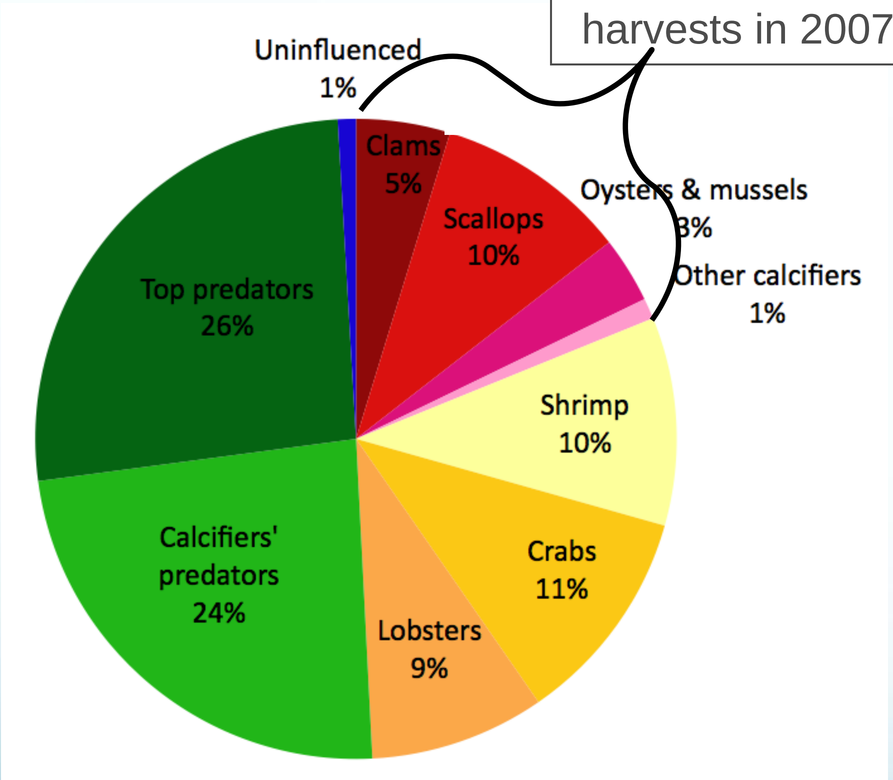
How to value ecosystem services?



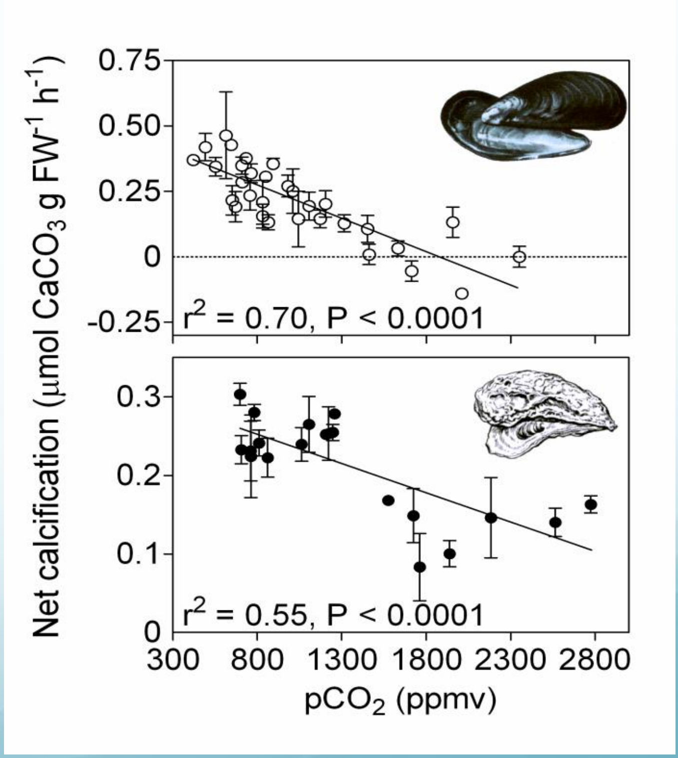
OA's economic impacts

U.S. mollusk harvests

Mollusks = $748M of U.S. ex-vessel harvests in 2007



- Assume a 0.1-0.2 unit pH decrease by 2060 = 6-25% lower harvests
  - Annual losses of $75-187M
  - NPV losses through 2060 of $1.7-10B



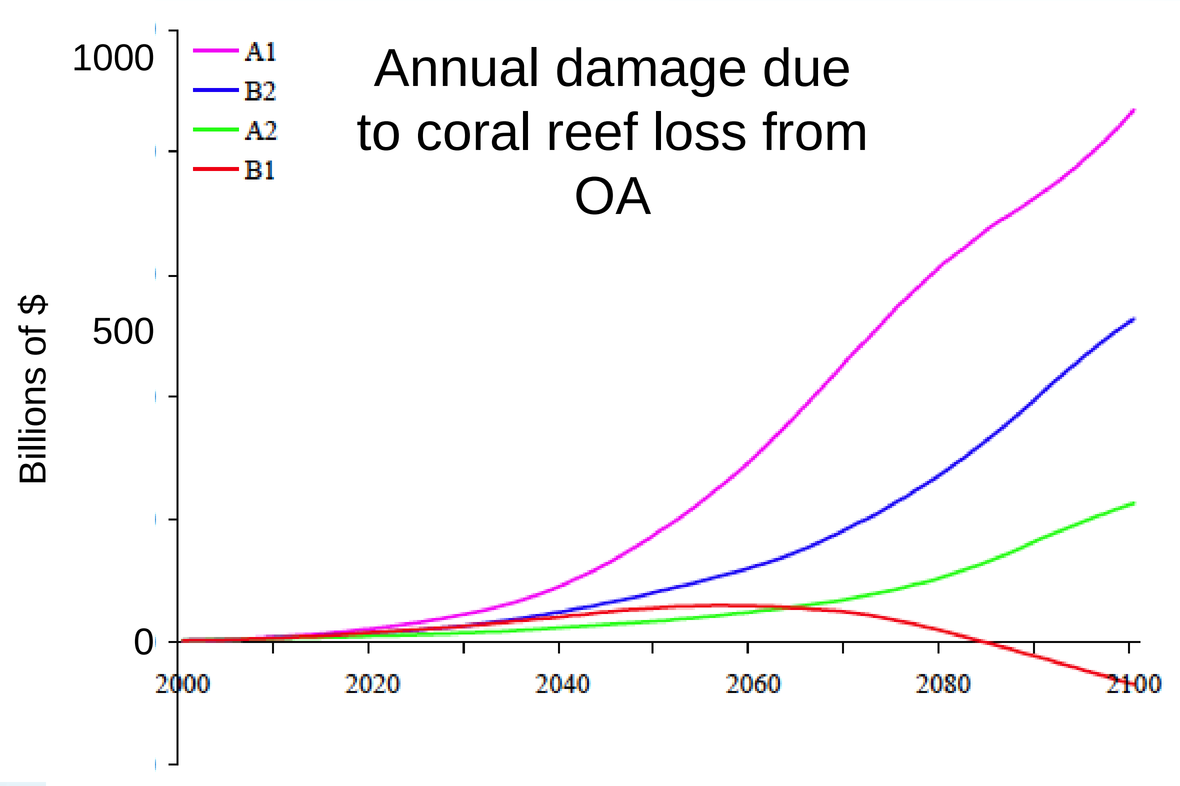
Cooley & Doney 2009 *ERL*

Gazeau et al., 2007; Green et al. L&O 2009

OA's economic impacts

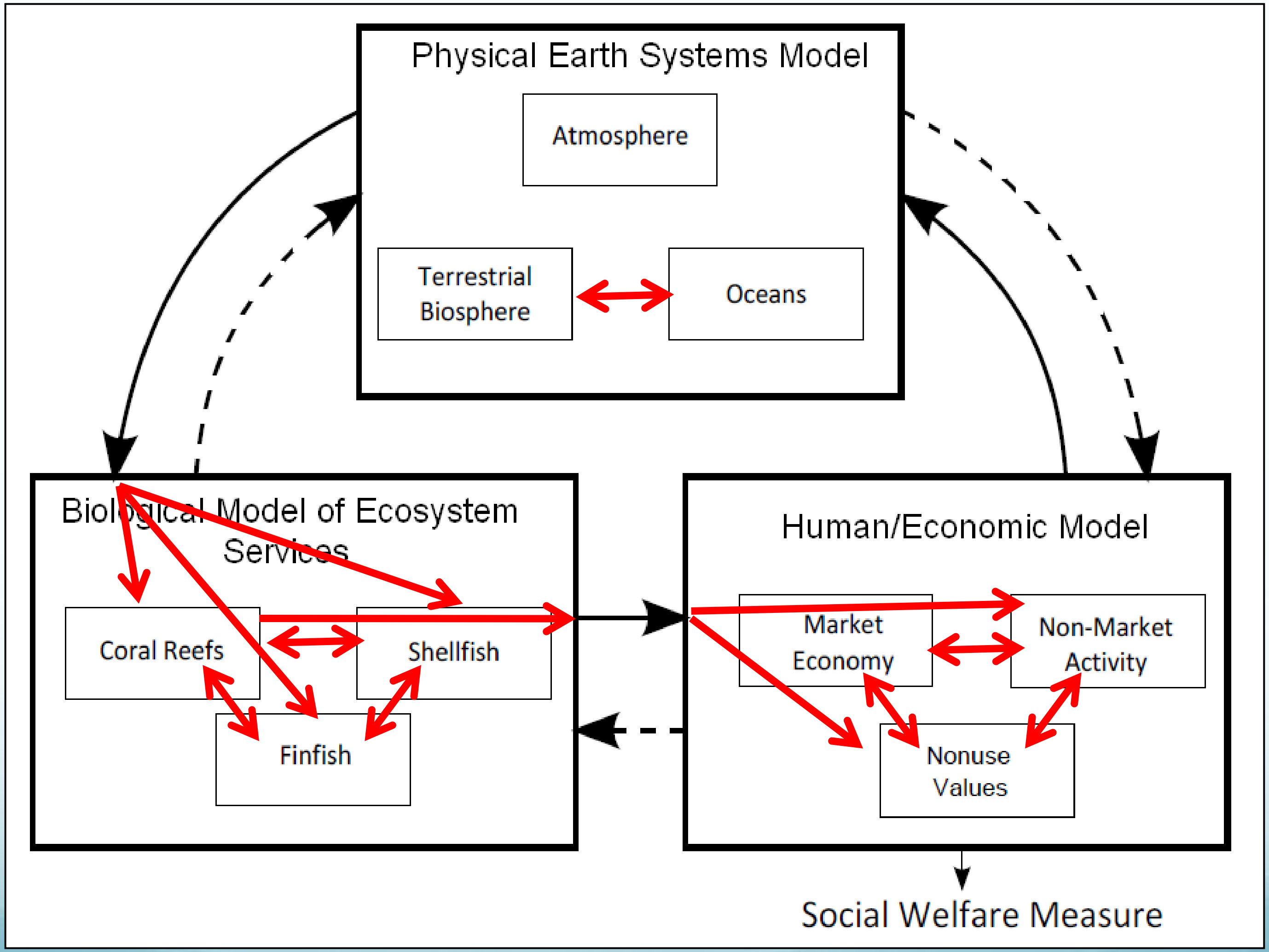
Coral reefs

- Value coral reefs via meta-regression
- More information needed on relation of coral cover to OA
- Results strongly driven by importance of reefs for tourism – nonmarket service underestimated?



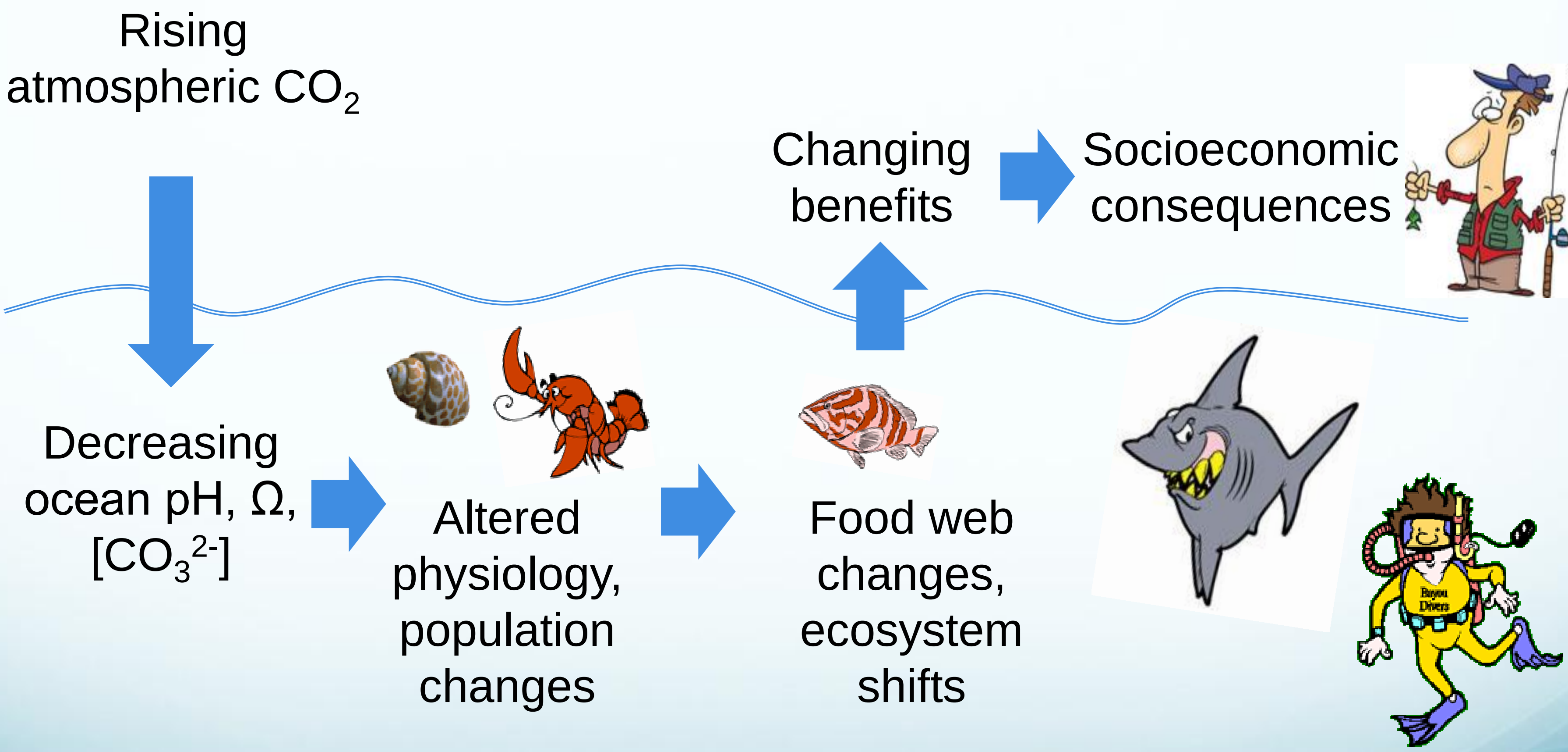
Brander et al. 2009, http://en.scientificcommons.org/41882916

Knowledge gaps for OA IAM



Schematic from C. Moore, EPA 2010

Uncertainty builds



Certainty scorecard

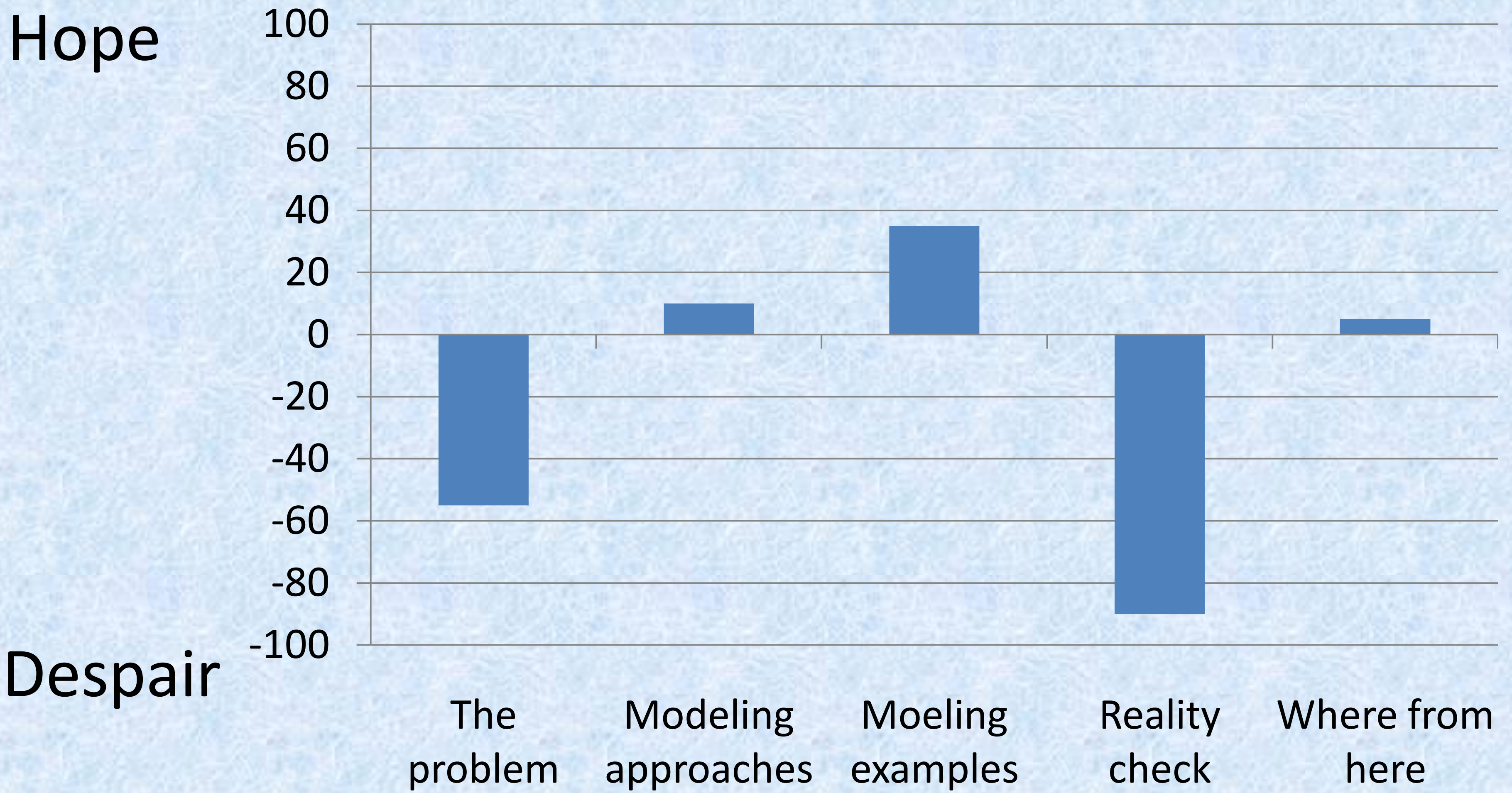
	Certainty	Data limited?	Methods limited?
Atmospheric CO2 rising	High		
Ocean pH, carbonate decreasing	High	✓	
Marine organisms affected	Medium	✓	✓
Ecosystems change	Medium/Low	✓	✓
Ecosystem services change	Low	✓	✓
Socioeconomic consequences	Low	✓	✓

Modeling Climate and Acidification Impacts on Fisheries, Aquaculture, and Other Marine Resources

Paul McElhany,
Research Ecologist
Northwest Fisheries
Science Center

Background Photo by Jared Figurski

Talk Outline



The Problem

Living Aquatic Resource Issues

- Capture fisheries
- Aquaculture
- Endangered species
- Tourism
- Shoreline protection
- Human Health

CO_2 Effects

- Growth and Survival
- Range shifts
- Stratification/circulation
  - Nutrients
  - Oxygen
  - Dispersal
- Sea level rise
- Acidification
- Storms
- Increased UV

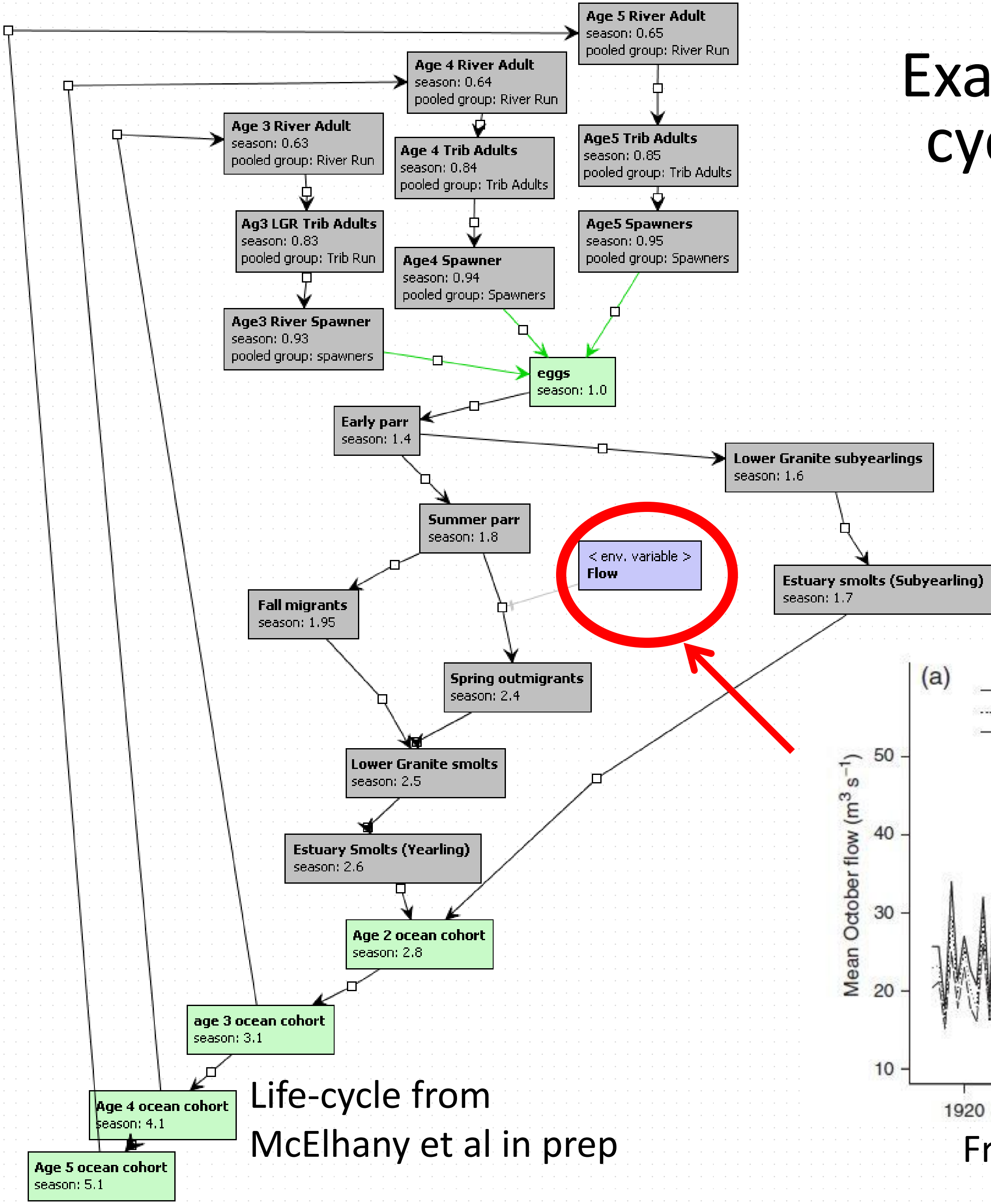
Model Flavors

- Fishery stock assessments
- Population Viability Analyses
- Food web/ecosystem models
- NPZ models
- Minimum realistic models
- Maximum unrealistic models
- Modeled range maps
- Individually-based models
- Life-cycle models
- Bioenergetics
- Expert systems

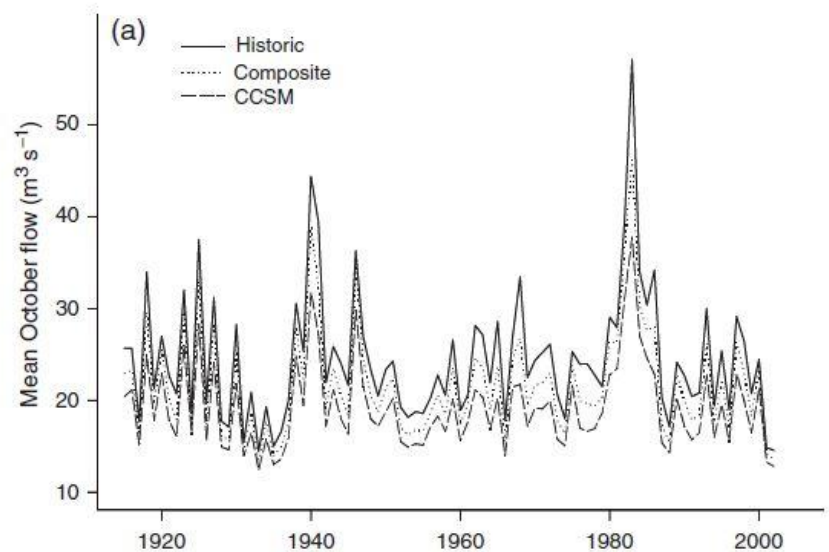
Incorporating CO_2: Down-scaling IPCC- class models

- Model Scales
  - Space
    - IPCC: typically 1° x 1° (~110 km latitude) or coarser
    - IPCC: Very poor on the coasts/nearshore, fronts and eddies
    - Biological scales: Sometimes meters mater
  - Time
    - IPCC: Does not resolve decadal scale patterns
    - Biological scales: annual and seasonal variation mater
- Key Features to down-scale
  - Temperature
  - Stratification/Circulation/Salinity
  - Storms
  - Sea level
  - Carbon Chemistry

Example 1: Salmon life-cycle, Climate change and stream flow



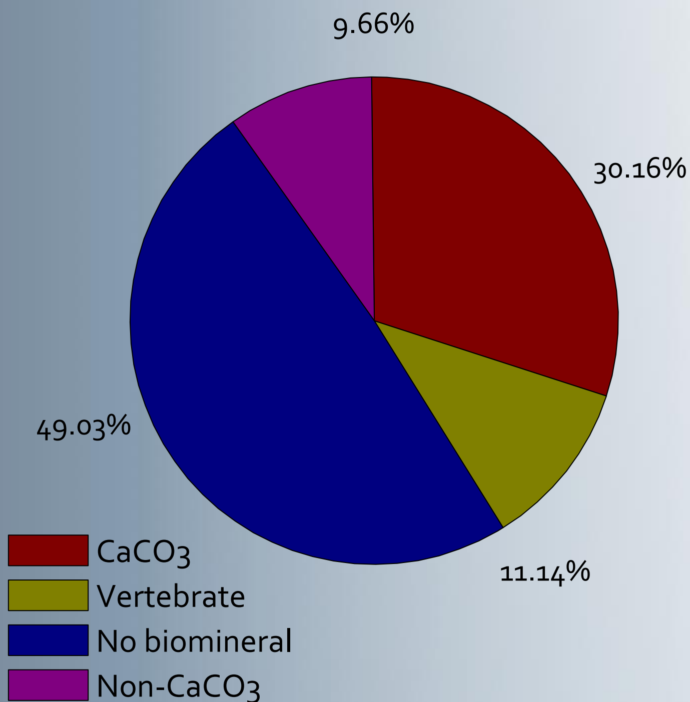
Life-cycle from McElhany et al in prep

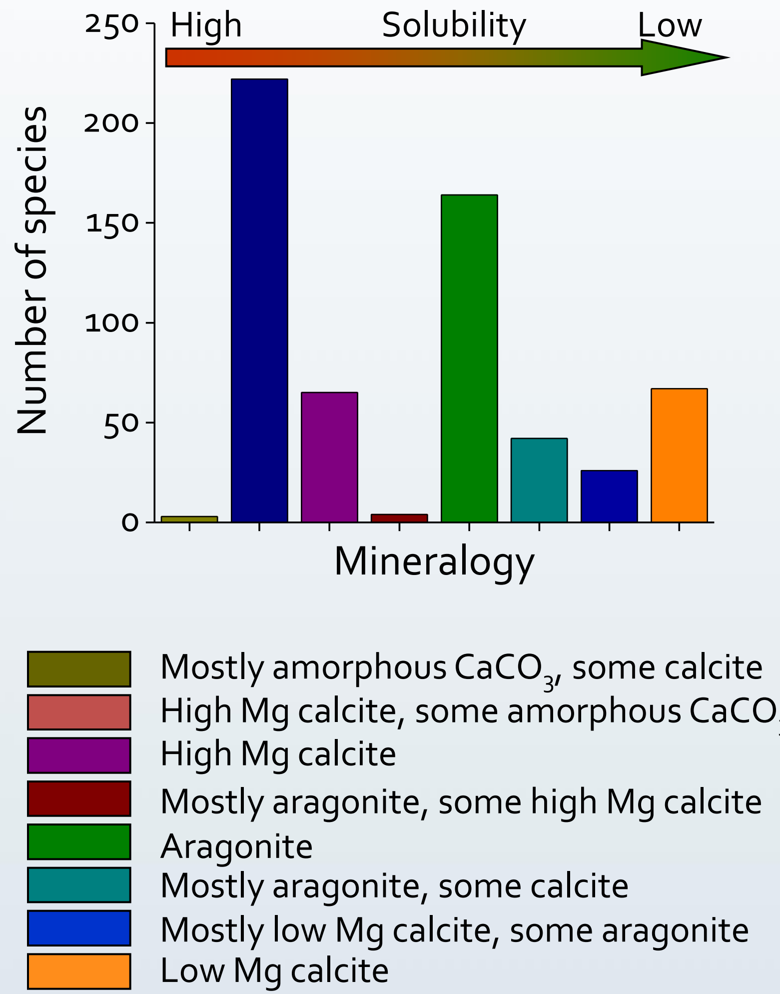


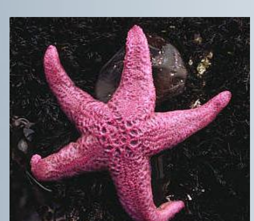
From Crozier et al. 2008

Example 2: Acidification in Puget Sound with Ecopath/Ecosim

Calcium carbonate mineralogy

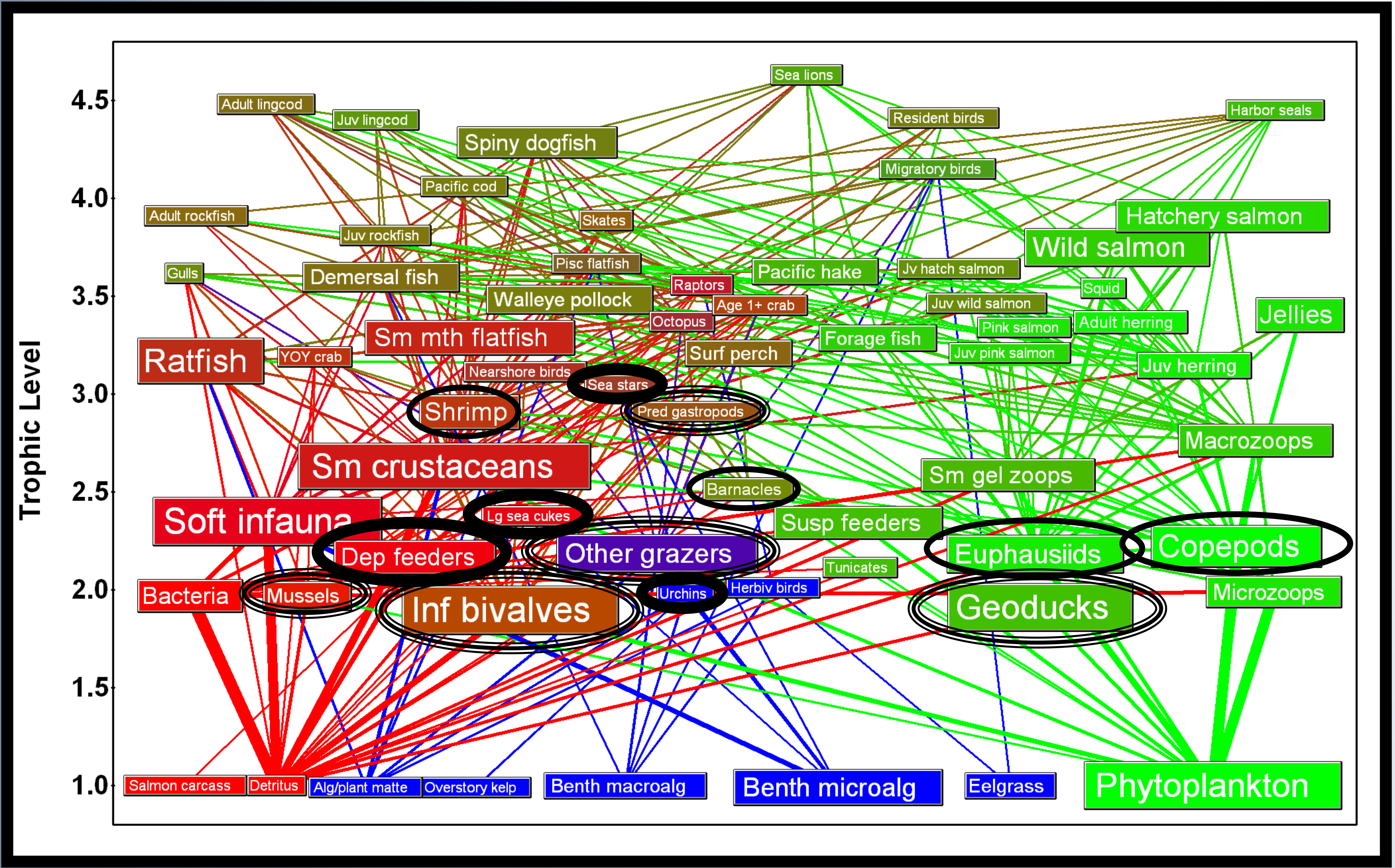






From Busch, Harvey and McElhany in prep

Puget Sound Ecosystem



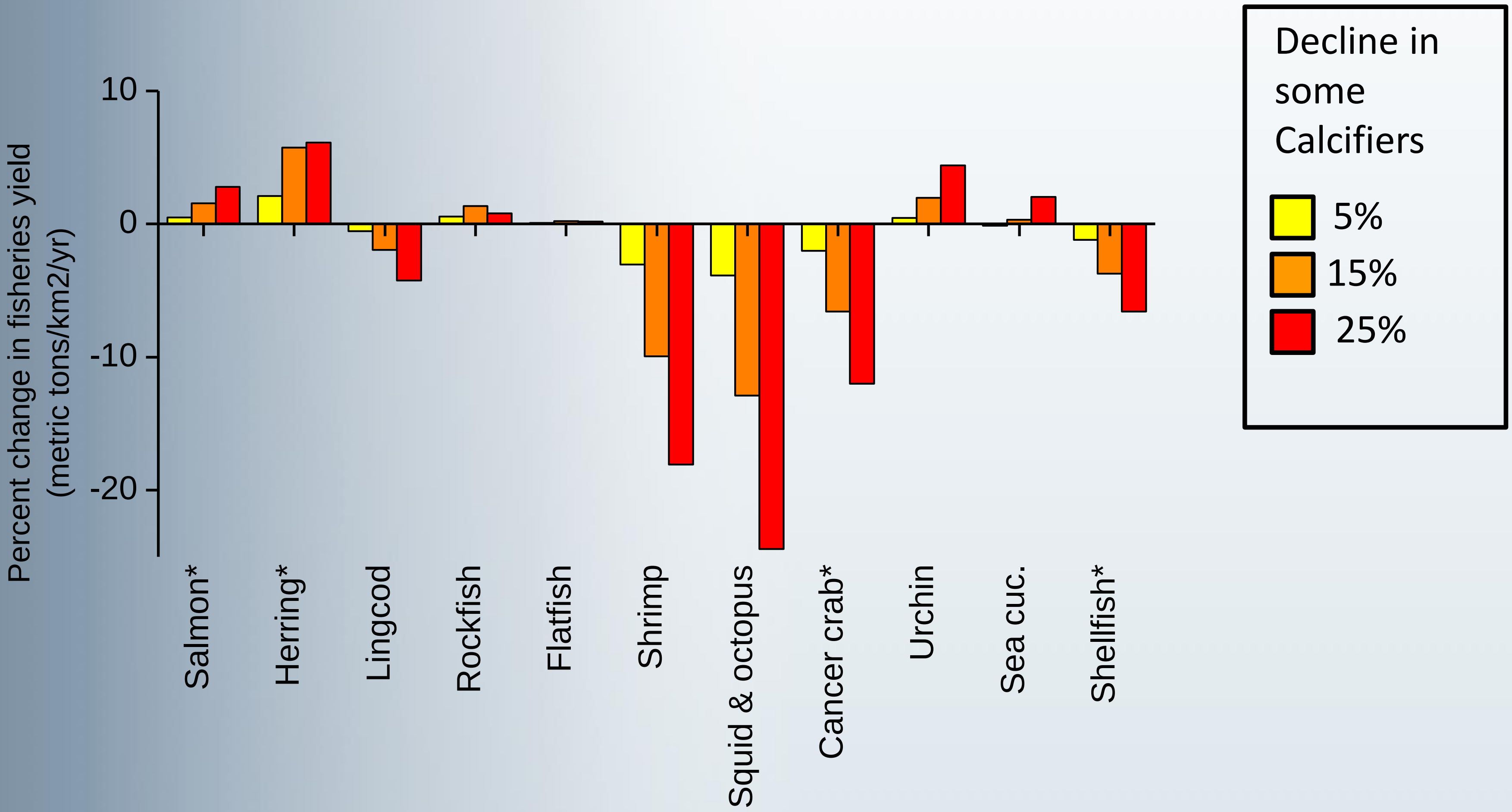
Busch, Harvey and McElhany in prep

“Because of their enormous size, the chemical composition of the open oceans, with the exception of lead, has not been greatly affected by human activities.”

Kates and Parris. **2003**. Long-term trends and a sustainability transition. Proceedings of the National Academy of Science

NWFSC OA Research Lab

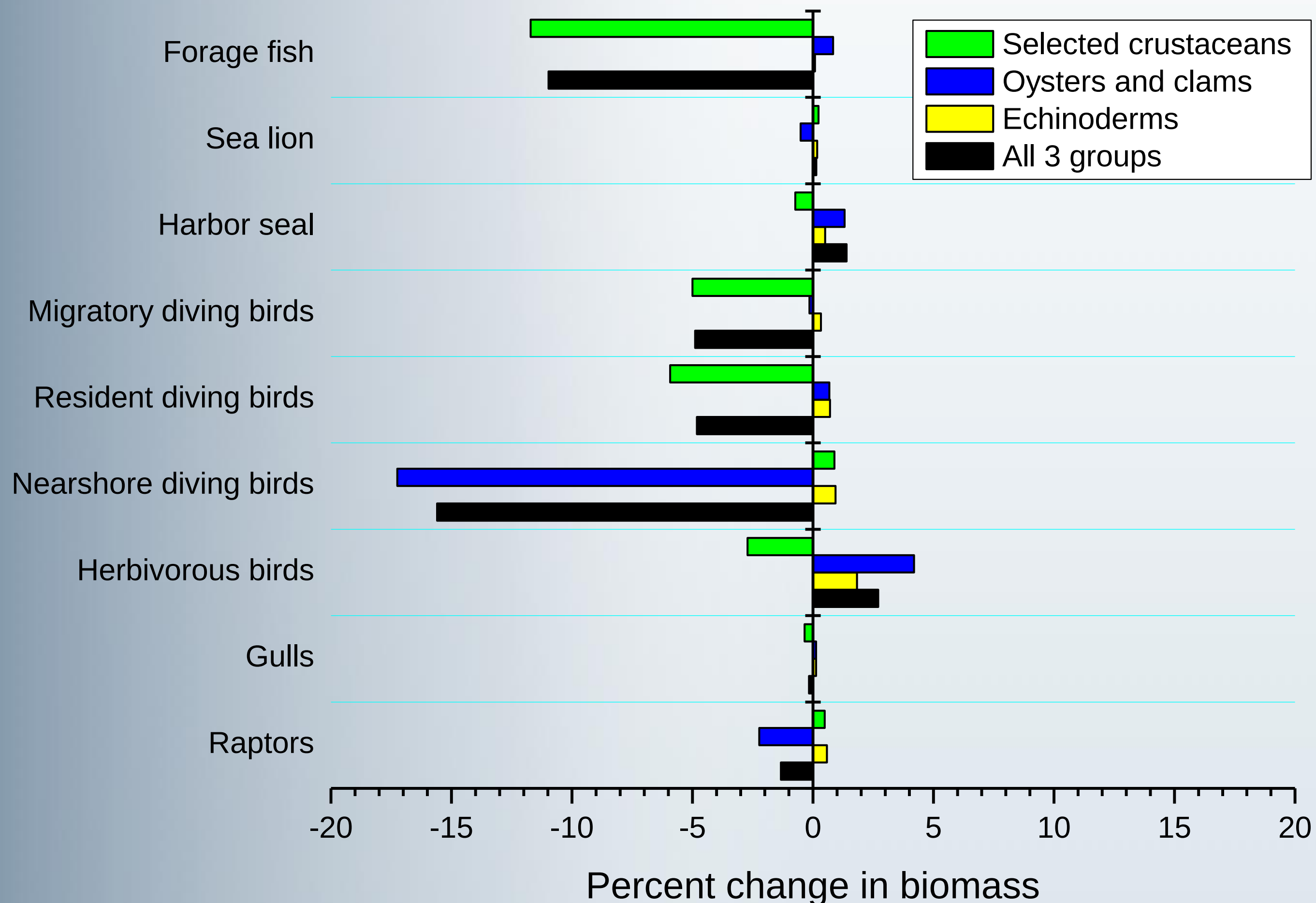
Impacts on Puget Sound Harvest?



Busch et al. in prep

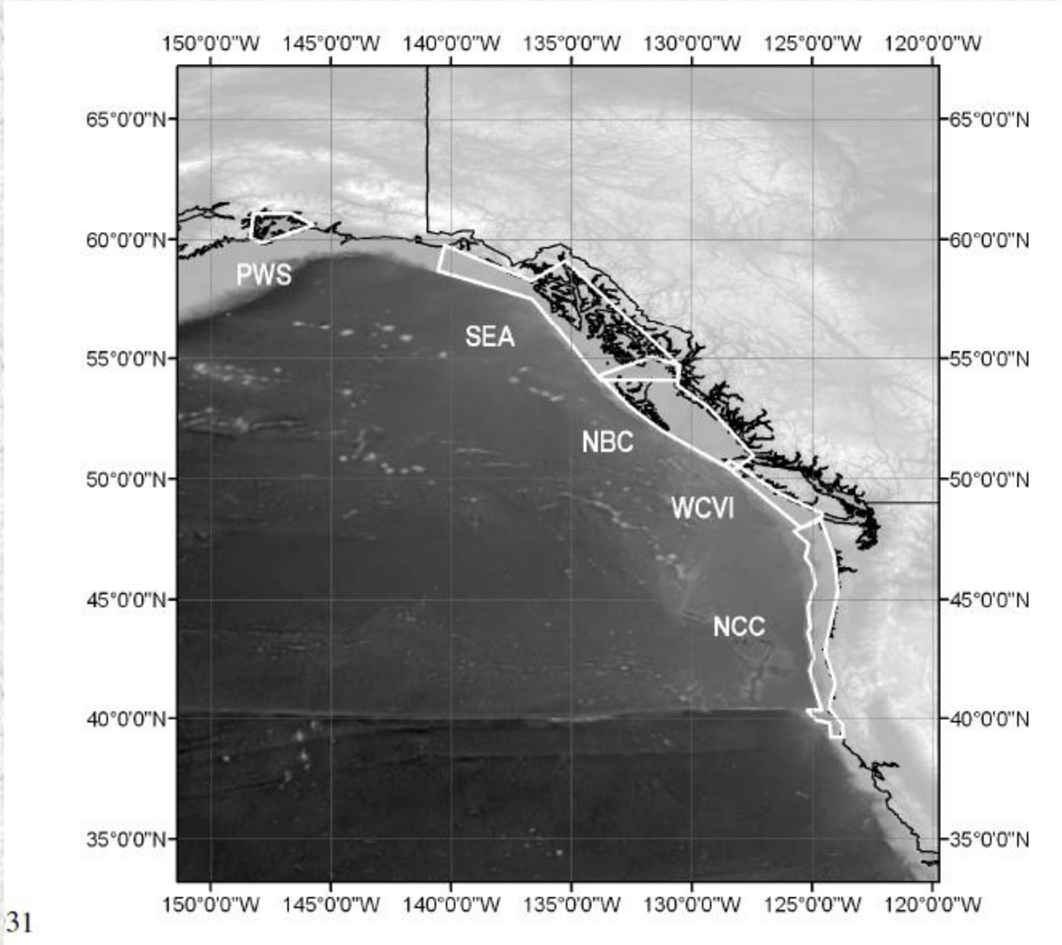
Impacts on Puget Sound Biomass?

From a 25% decline in some calcifiers



Busch et al. in prep

Example 3: California Current, Climate and OA with EwE (Ainsworth et al.)



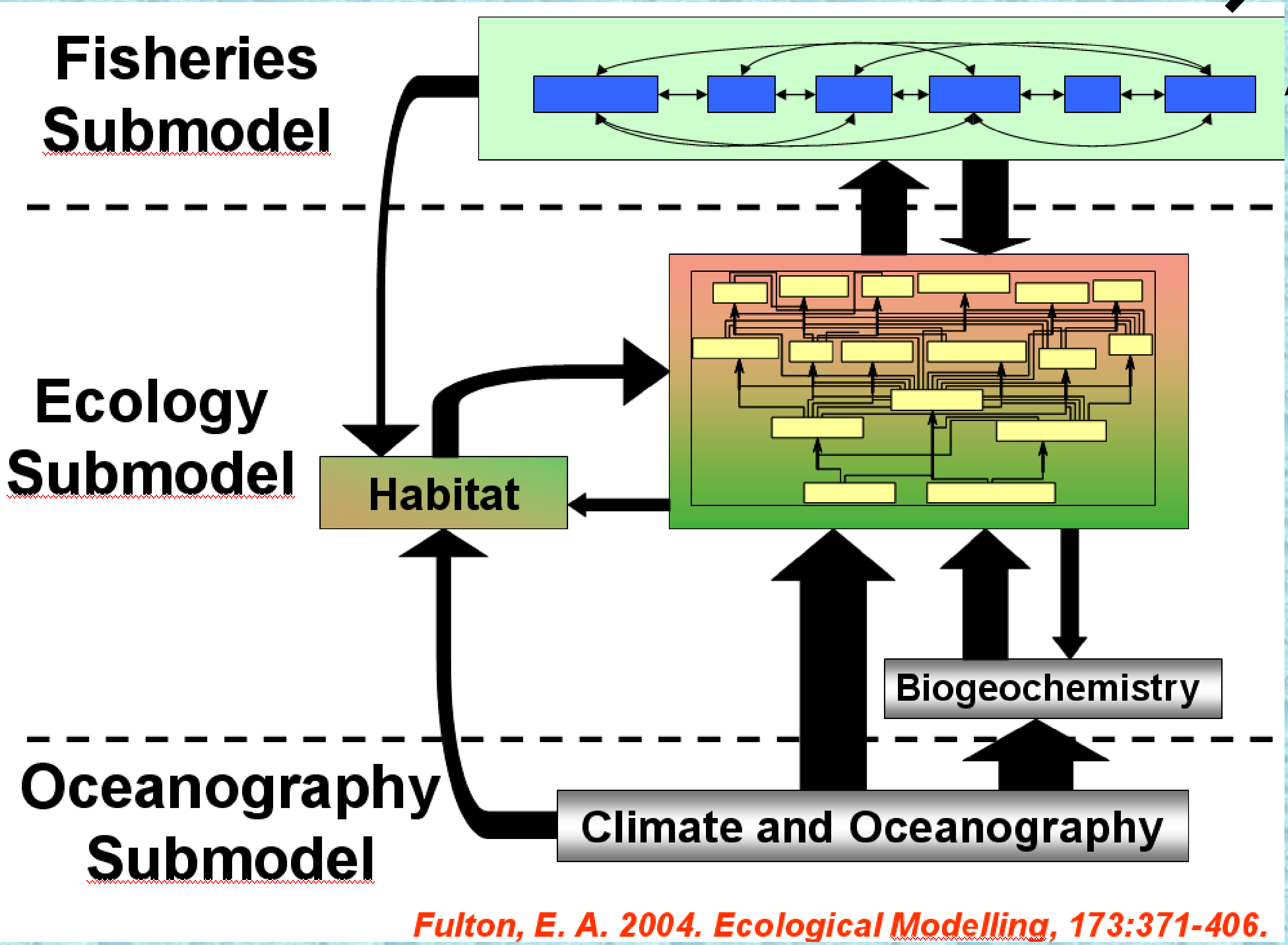
California Current Climate Effects

- Primary productivity (from GFDL ESM2.1)
- Biogeographic range shifts (from Cheung et al.)
- Zooplankton size structure (Moran 2009)
- Ocean acidification (Busch et al. review)
- De-oxygenation (Whitney 2007)

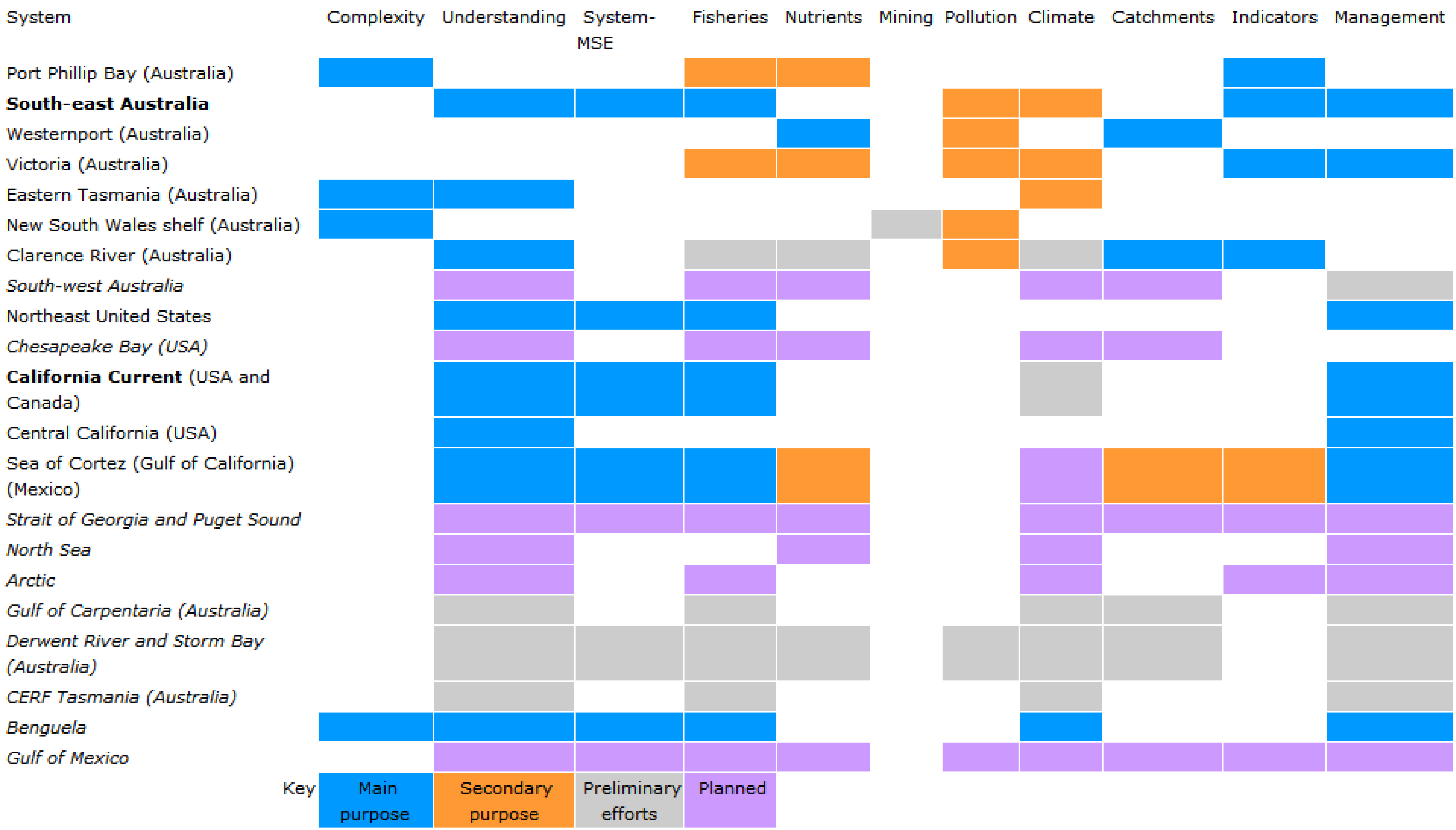
Result Summary

- General decline in fisheries, especially with all climate effects
- Range shifts biggest impact

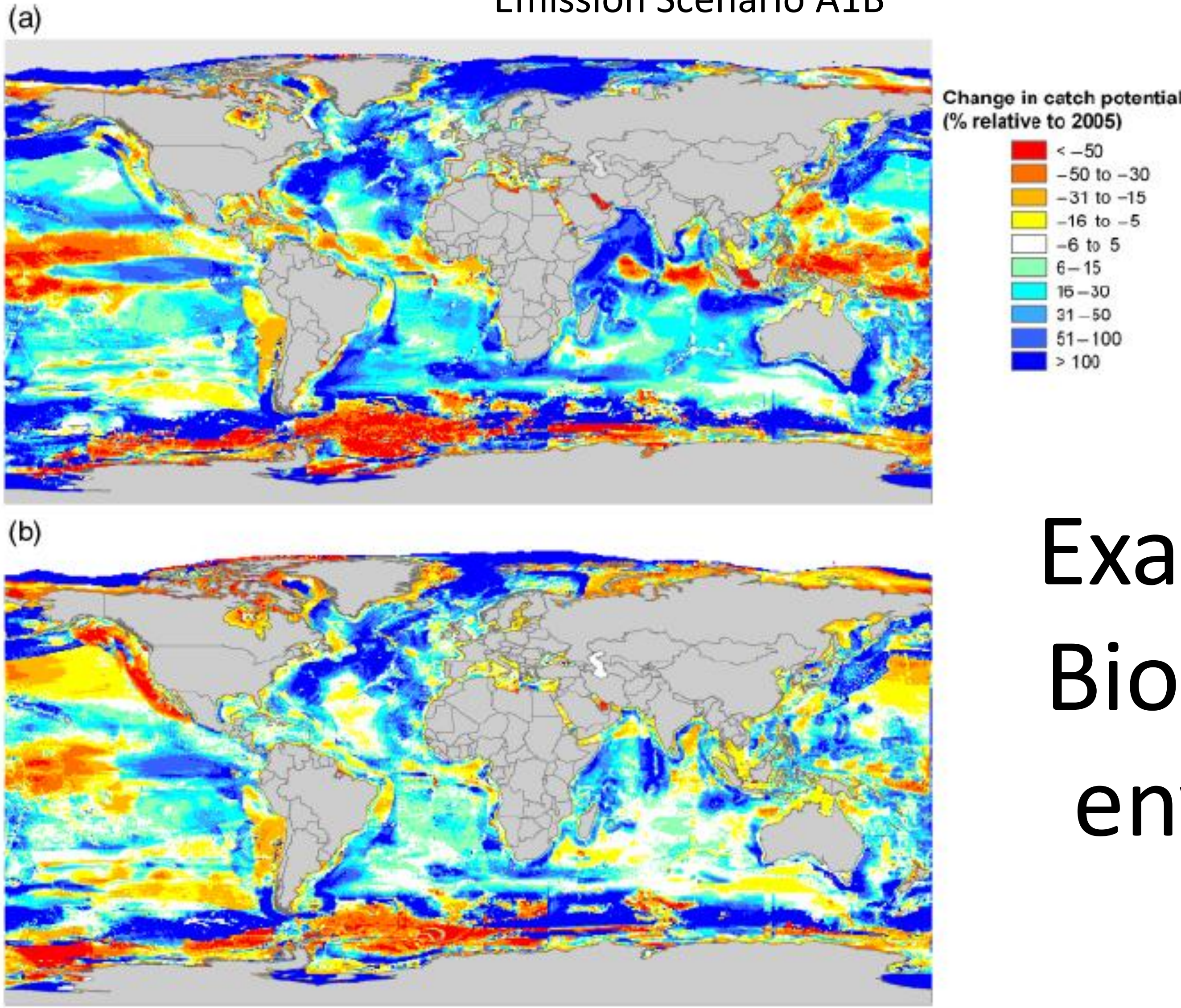
Example 4: Atlantis

Atlantis Applications



Emission Scenario A1B

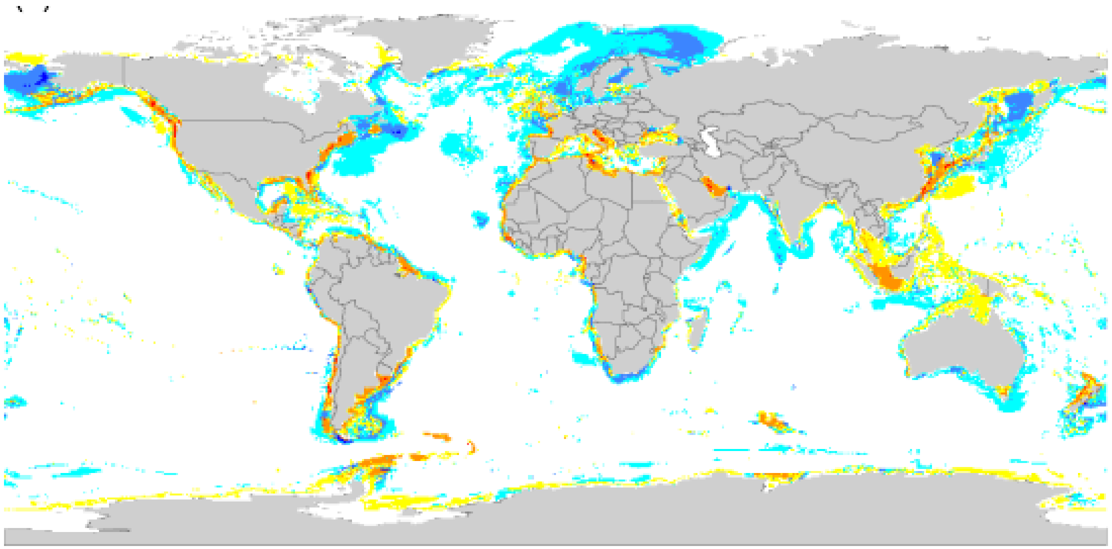


2000 Emission Scenario

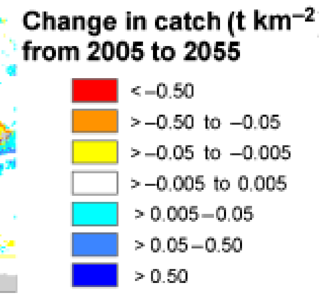
Example 5: Bioclimate envelope

From Cheung et al. 2009

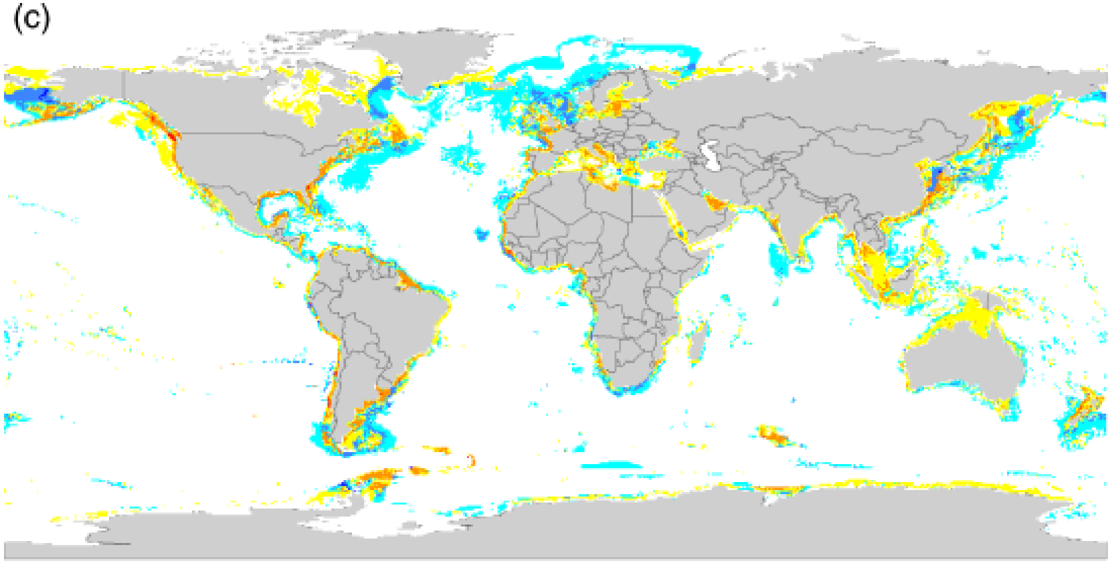
Projected Change in Catch



Emission Scenario A1B



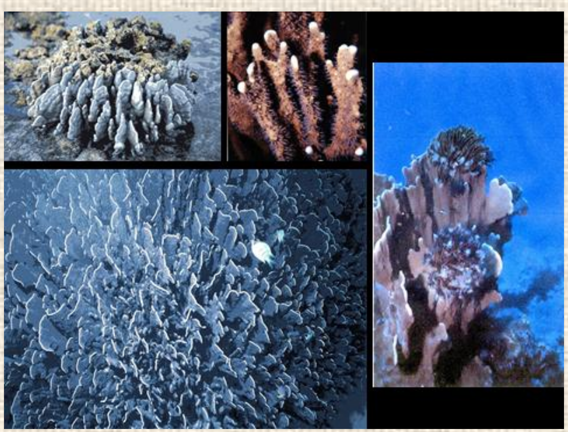
(c)

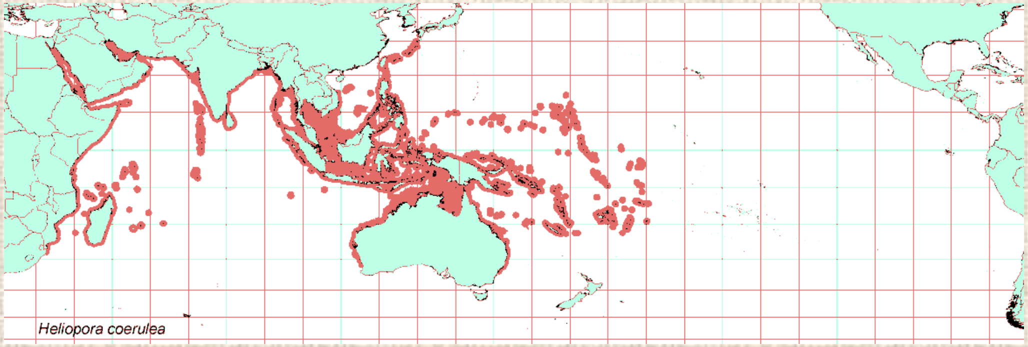


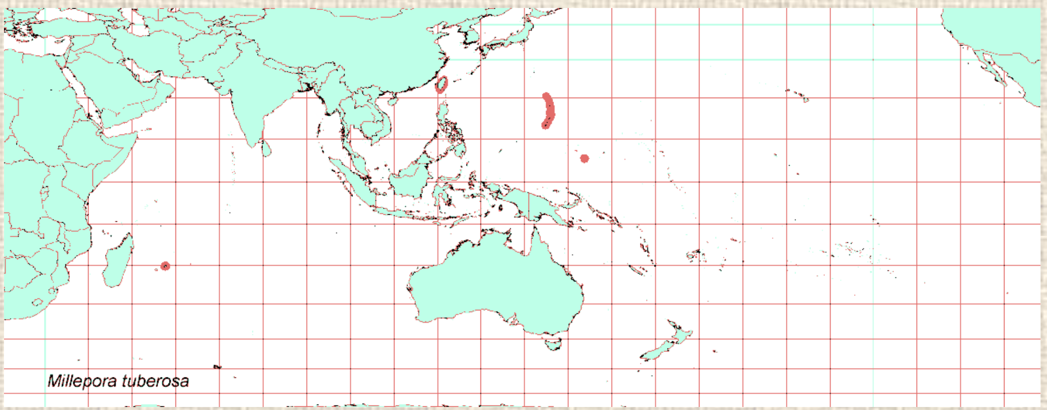
2000 Emission Scenario

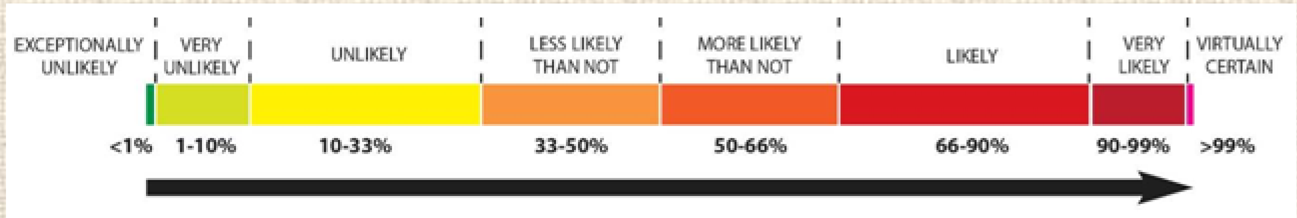
From Cheung et al. 2009

Example 6: Extinction risk for 82 species of tropical corals

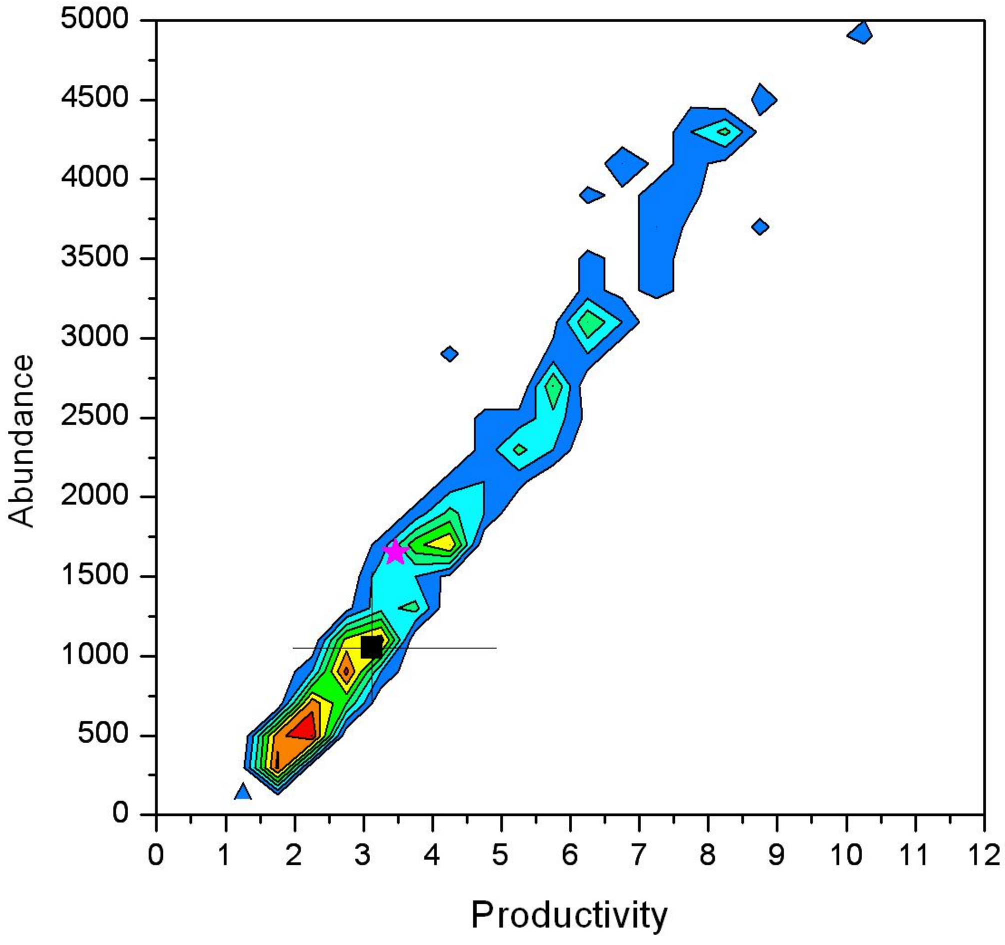








Incorporating Uncertainty



Uncertainty changes mean, not just the range

From McElhany et al. 2010

Reality Check – Some big questions

- Florida – yes or no?
- Gulf stream – same
- Increased stratification – how much, where, effect?
- Upwelling – same
- Decadal oscillations (“regime shifts”)???
- Adaptation to OA and temp?
- Ice ecosystems?
- Rainfall changes and freshwater systems – where, how much
- Where will fishing get better?

Details Matter

- Species differences
- Species interactions (predator-prey mismatch)
- Phenology
- Synergistic effects
- Short term variability
- Local circulation
- Lab studies don’t scale to ecosystems

Moving Forward: Coarse scale impact assessment

- Back Of Envelope (BOE) estimates
- Three Approaches:
  - Bioclimate envelope as key first pass estimates
  - Minimum realistic models on high value fisheries
  - Ecosystem/foodweb to look for interactions
- Resolution of big climate questions

Some References

- Cheung et al. 2009. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Global Change Biology.
- Kevern et al. (ed). 2009. Climate change implications for fisheries and aquaculture. FAO.
- Stock et al. in press. On the use of IPCC-class models to assess the impact of climate on Living Marine Resources. Progress in Oceanography.

Modeling economic impacts of climate change and ocean acidification to fisheries

David Finnoff (University of Wyoming)

Abstract

Ocean acidification appears to have potential to be a significant problem. Past declines in ocean surface pH have been linked to mass extinction events (Guinotte and Fabry, 2008). While I am not an expert in the science, the issue starts with declines in pH (increased acidity) causing a reduction in carbonate ion concentration which in turn causes a reduction in calcium carbonate saturation. This has impacts on marine organisms that are calcifiers and essentially requires marine calcifying organisms to use more energy to form biogenic calcium carbonate (Guinotte and Fabry, 2008). The observable consequences are thought to be hampered reef formation of corals, algaes and hampered shell formation of oysters, clams and crabs (although there are varying consequences on species depending on studies as shown by Dr. Cooley).

There has been little work assessing the economic consequences of ocean acidification. The one notable paper is that of Cooley and Doney (2009). In this paper the authors calculated potential revenue losses for the U.S.A. from decreased mollusk harvests. If reductions of 6%–25% from 2007 level of harvests were to occur in 2009, the authors calculate $75–187 million in direct revenue would be lost each year into the future, with a net NPV loss of $1.7–10 billion through 2060. However it needs to be noted that these values were calculated using what are commonly termed as replacement cost or engineering cost estimates. From an economic viewpoint, there is no direct connection between replacement costs and a useful welfare measure.

From an economic viewpoint, if ocean acidification affects the provisioning of ecosystem services, it can result in lost consumer surplus (which are the opportunity costs to consumers). Consumer surplus is the benefit to consumers of a market outcome and accrue whenever consumers pay less than their maximum willingness to pay for that unit of a good.

Market prices simply capture the relative rate at which the market is willing to exchange one good for another. The method employed by Cooley and Doney (2009) is the product of market price and a change in quantity, or engineering cost estimates. If the reduction in mollusk harvests are given by the difference in harvests from Q_0 to Q_1 as shown in Figure 1 evaluated at the constant price P_0:

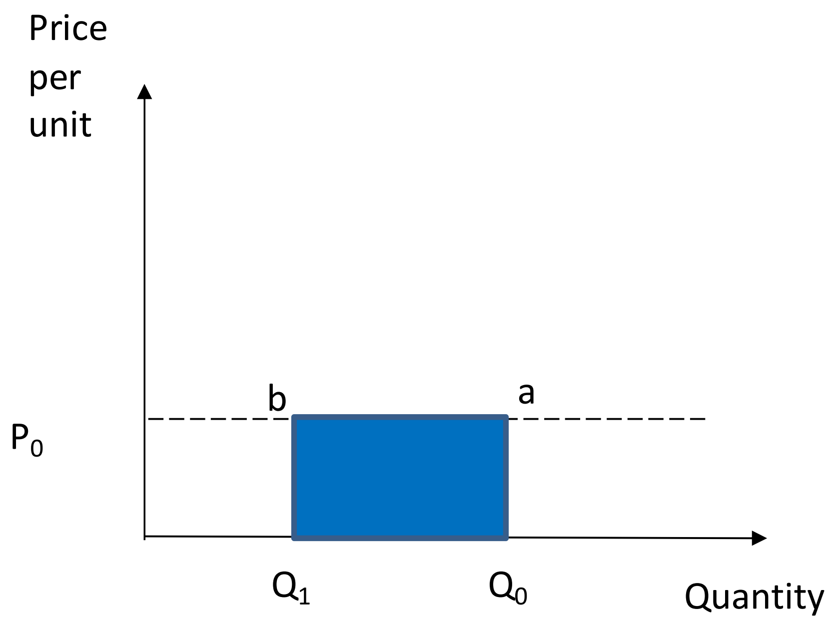


Figure 1 Replacement cost estimates

The lost revenues from ocean acidification are calculated (area Q_1 Q_0ab, shaded area in blue). Values calculated in this manner tend to be rejected as they have no relationship to the economically relevant surplus measures. Figure 2 illustrates the lost consumer surplus (area P_0P_1ca, shaded area in red) associated with the same reduction in harvests if price increases from P_0 to P_1 with the harvest reduction Q_0 to Q_1:

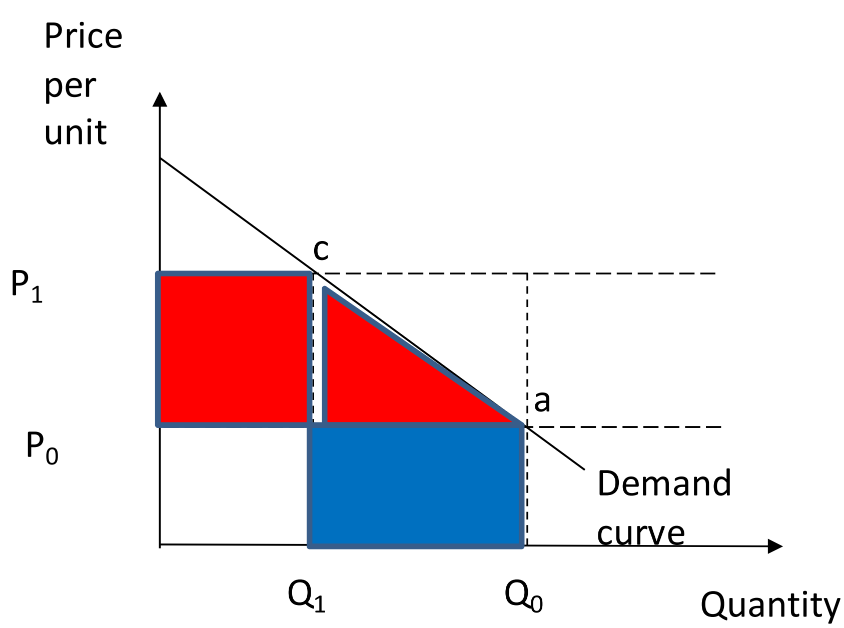


Figure 2 Consumer surplus estimates

As Figure 2 illustrates there is no direction relationship between the replacement cost estimate and the loss in consumer surplus. The replacement cost estimates do not measure or even approximate economic welfare (see Bockstael et al. 2000). In addition, they omit key interactions within the economy and between the economy and nature (Finnoff & Tschirhart 2008). However, applying an economic approach can be a challenge because it requires measuring these surplus measures, which requires more information than just market prices and quantities.

To apply an economic approach to the problem, it helps to consider the problem as one of a class of One of a class of "Materials Damages" problems studied in detail by Tom Crocker 25 years ago (see a review of the research effort for the EPA report archived at http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0043.pdf/$file/EE-0043.pdf). In this work Crocker and his colleagues made the salient point that human welfare is dependent on biological systems (material environment) that provide critical inputs to human activity. If there are damages or improvements in material environment then there will be welfare changes.

Adams and Crocker (1991) laid out three basic steps to assess materials damage from environmental changes. The first step is to provide an understanding of how the environmental change perturbs production and consumption opportunity sets. The second was then to determine the input and output market prices changes in response to the perturbations in opportunity sets. The third was to the document all the adaptations humans can engage in to minimize losses or maximize gains from changes in opportunities and prices.

In general, changes in production opportunities from perturbations in provisioning of ecosystem services (ES) change producers production possibilities by the availability and combinations of ES input sets (i.e. species compositions and densities). In turn this also affects output sets as there may be fewer of some economically relevant species and potentially more of others. If the environmental degradation reduces production possibilities then there will be less choice, higher costs and lower profits. Regardless Adams and Crocker (1991) point out that human objective functions and behavioral conditions remain the same in that firms still choose cost minimizing input combinations.

Similarly in consumption, perturbations in provisioning of ES may change costs facing households directly or indirectly with corresponding welfare consequences. Again the underlying economic problem remains the same with households choosing utility maximizing combinations of goods and services given their income given the perturbations in provisioning of ES.

The implication is that standard economic models can be used if the environmental perturbations can be reliably brought into economic analysis. This is a primary challenge facing research in this area. To bring the environmental changes into economic analysis there is a basic choice in the representation of the natural system. On the one hand the assessment could employ a reduced form representation of the natural system, reducing the entire natural system into one or two indicators (i.e. species). These approaches are commonly seen in the bioeconomic literature (see Massey et al 2006, Smith 2007). They are easy to fit to limited data and are typically thought to give a good overview of general processes. However, it has been shown that aggregation (into a reduced form) can cause errors in economic estimates (Kopp and Smith, 1980). On the other hand the natural system can be represented by a detailed, or structural model (see Finnoff and Tschirhart 2008). Structural representations can represent critical details explicitly and capture the complex adaptive nature of natural systems. However, it has been shown that there are rapidly declining marginal returns to the inclusion of additional natural science information (Adams, Crocker and Katz, 1984). The question then becomes what is the appropriate balance of reality and tractability in the analysis?

One organizing principle that has roots in Tom Crocker's work is the potential for non-convexities in natural system phenomena (see for example Crocker and Forester, 1981 and Brown et al. 2010). If the natural system is reasonably convex, then environmental perturbations will have monotonic effects that can be well represented with a reduced from representation. But if there are pervasive non-convexities then a high level of abstraction may lead to trouble and it may well be necessary for the assessor to know the entire possibilities surface.

The point is rather obvious if one considers the standard way an economist might consider correcting a materials damage problem (to correct the problem one has to understand the welfare consequences making an economic assessment one part of a corrective policy). Figure 3 illustrates a hypothetical setting relating (loosely) to the problem of ocean acidification and a simple adaptation of Crocker and Forester (1981). In the top panel, marginal control costs and marginal damages of acidification are presented as downward and upward sloping functions of pH (acidity increases to the right of the horizontal axis and decreases to the left). Economic theory would dictate that as there are costs of control and damages that there is a single point of balance between the two marginal effects – a point at which the net benefits to society of a plan of action are maximized (bottom panel). To find the optimal point all one needs is information on marginal damages and marginal control costs to determine how to maximize social net benefits.

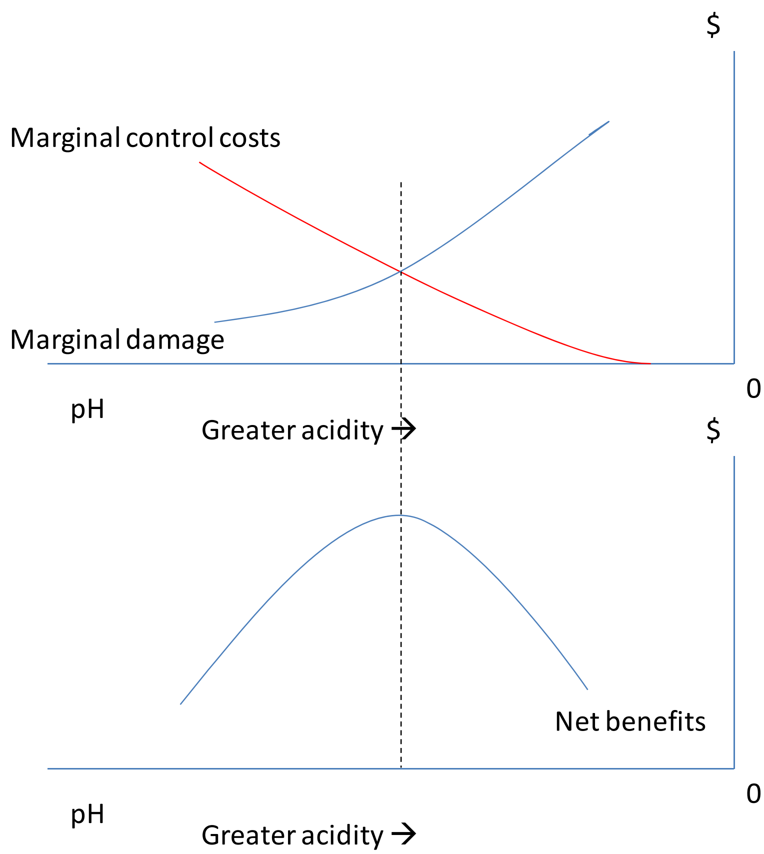


Figure 3. Optimal acidification in the standard setting

However, in many cases (see Crocker and Forester 1981) marginal damages or marginal control costs may not be monotonically related to the environmental state. Figure 4 demonstrates the case Crocker and Forester found for terrestrial acid deposition. Here, there are serious non convexities in marginal damages. The implications are then that there is the possibility for multiple equilibria and having to differentiate between local and global optimal. For example, as shown in Figure 4, without a knowledge of the entire damage and cost functions would the researcher be able to determine which of the equilibrium points A, B, or C would be globally optimal. In addition, unlike the standard setting, how exactly natural and economic adjustments are to be made to bring the system into equilibrium are not as clear. For example, in the region between A and B the marginal damages of acidification exceed the marginal control costs, signally that a reduction in pH is optimal, directing the situation towards point A. However, to the right of point B the reverse is true, signally that an increase in pH is optimal. This would direct the situation towards point B which would only be appropriate if it were a global maximum. If only a local max this would be problematic (to say nothing of the highly acidic end state). It appears that an expansion of the scope of analysis is necessary as marginal comparisons alone (of marginal damages to marginal control costs) are insufficient to signal how to maximize social net benefits. In these settings it is likely necessary to know the entire surface (across environmental change) to locate the global optimum and understand the signals provided by marginal measures.

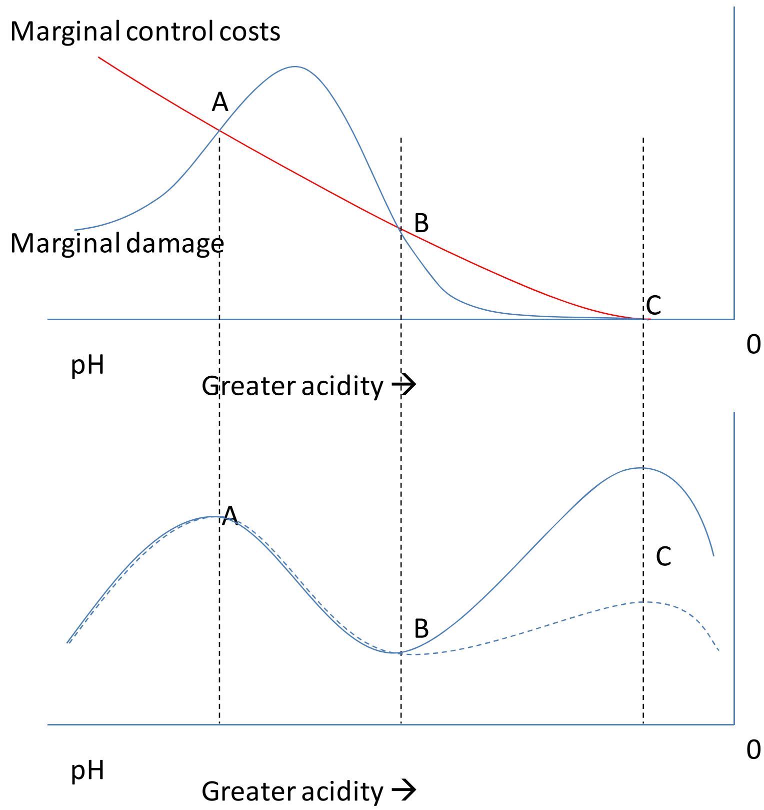


Figure 4. Acidification with non-convexity

Of course then the question becomes is there the potential for non-convexities with ocean acidification?

Using an extension of a Bering Sea ecosystem model developed in Finnoff and Tschirhart (2008) in work for the EPA and National marine fisheries service (illustrated by Figure 5) the consequences of ocean acidification were simulated in a very ad-hoc fashion. Under the assumption that acidification only influenced the commercially important crab stocks, the ad hoc assumption was made in the model that acidification increases variable respiration requirements of crabs for any level of biomass consumption. The process could be expected to directly affect more species but the point is just to illustrate the potential ecosystem consequences.

Using 3 arbitrarily chosen severities (1 being the most severe and 3 the least) and assuming that the full effect would take time to unfold the model was used to generate multi-species growth functions for ecosystem species in the presence of acidification. Figure 6 presents the growth functions generated for three commercially important species, crabs, pacific cod and arrow tooth flounder under a benchmark of no acidification, low acidification, moderate acidification and high acidification. The growth functions simply document the "surplus" production available or growth (vertical axis) at any level of stock (horizontal axis) that could be appropriated by humans and the system remain in equilibrium (a multispecies interpretation of bioeconomic yields)

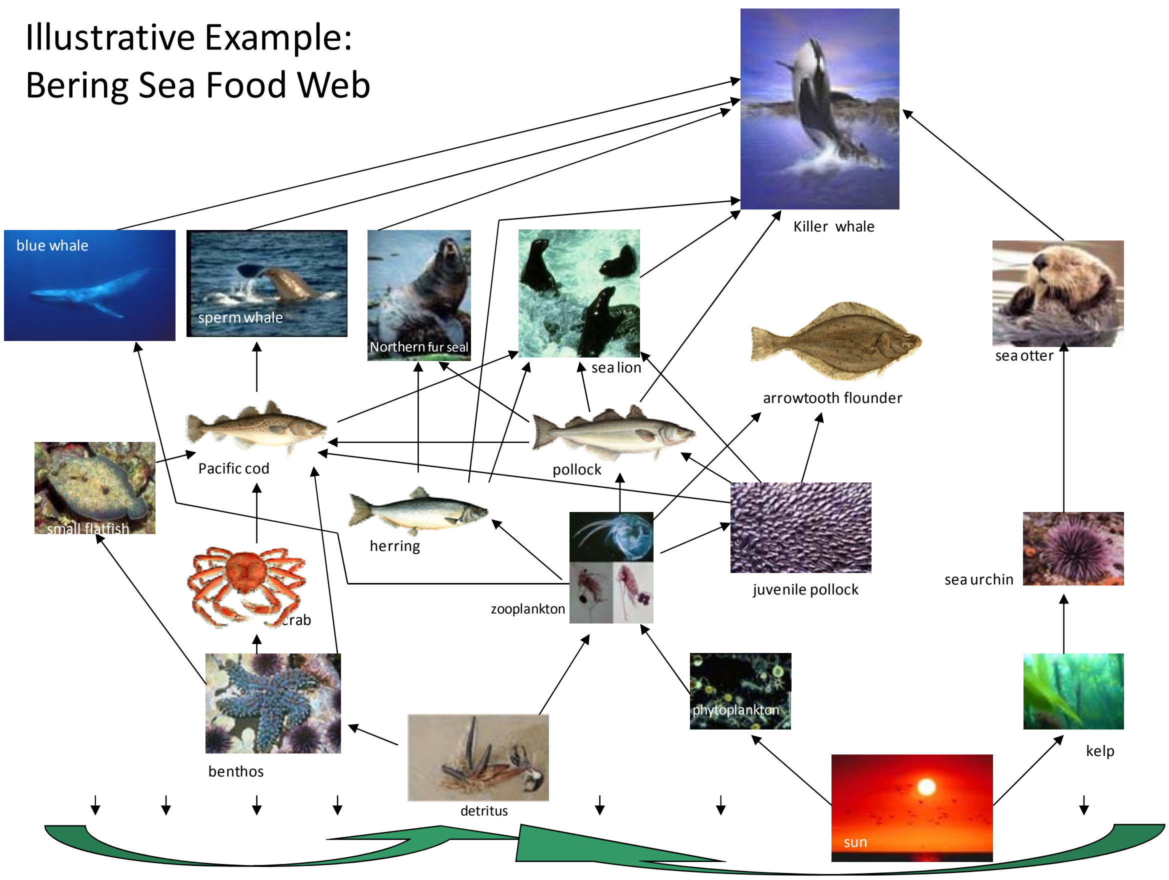


Figure 5

What is striking about Figure 6 is that for crabs alone there are non-monotonic changes from ocean acidification. For the low to moderate levels of acidification (levels 2 and 3) the multispecies carrying capacity of crabs (where the growth curves cut the horizontal axes) increases. In the absence of human harvests crab populations might increase at these low levels of acidification! This is due to the food web repercussions of acidification which see differential effects on predators (cod) and prey (bethos) which reverberate throughout the ecosystem. High levels of acidification (level 1) here would lead to extinction of crabs.

For other commercially exploited species that are directly related through a direct predator prey relationship, such as cod, a low level of acidification finds the carrying capacity only slightly altered but there are significant declines at moderate and high levels (where the moderate and high lines overlay one another). Arrowtooth flounder (ATF) are also commercially exploited yet are more distantly related in the food web. They only experience minor effects on their carrying capacity across the levels of acidification. However, for each of these commercially exploited species there are significant declines in surplus growth (sustainably harvestable biomass).

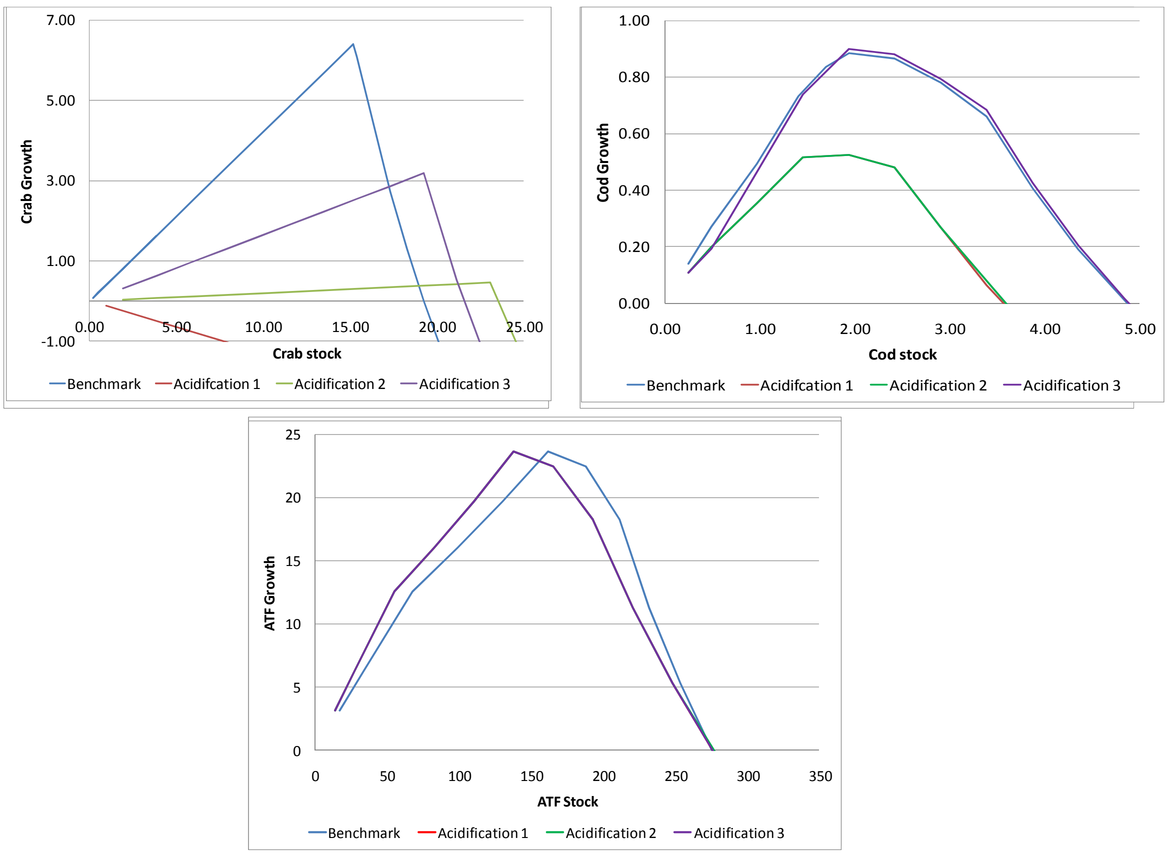


Figure 6 Selected growth curves for commercially exploited species

There are also effects on charismatic mammals that could be expected to have significant non-market values (Finnoff and Tschirhart, 2008) yet are only indirectly related to crabs in the ecosystem. Figure 7 presents growth curves for stellar sea lions (SSL) and sperm whales (SW). Sperm whales are more directly related to the effects on crabs than sea lions yet both have effects on their carrying capacities and growth (the moderate and high acidification curves overlay one another).

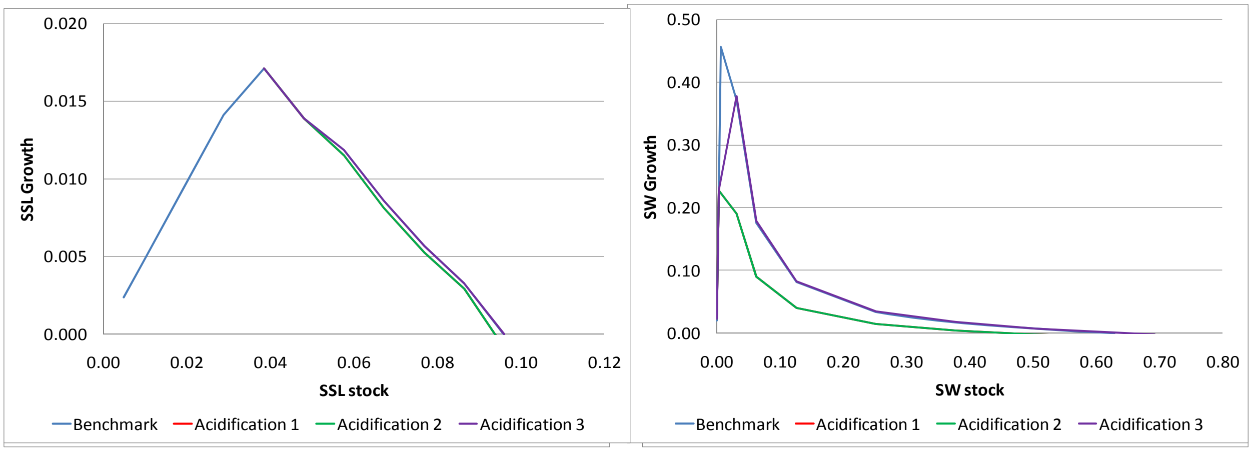


Figure 7 Selected growth curves for charismatic mammals

In sum, the consequences from acidification reverberate across system in varying degrees and magnitudes. There definitely seems to be the potential for non-convexities. As shown in the above figures, the negative shock of acidification on the crab optimization problem can result in higher carrying capacities yet less surplus growth. The changes are not typically monotonic. The implications for bioeconomic harvests of fish and crab is that they will likely be affected in varying degrees and magnitudes depending on their location in the food web. There are also perturbations in non-harvested stocks in varying degrees depending on their location in the foodweb.

Regardless of the accuracy of these results, they point to the complexity in assessing the changes in opportunity sets posed by acidification. To assess these or similar consequences an evaluation mechanism would need to be able to assess changes in flows (harvests of commercially exploited species) and stocks (changes in charismatic mammals) simultaneously. There is much the same reality versus tractability debate in the assessment mechanism as in the inclusion of ecological detail.

One organizing lens is whether a reduced form (partial equilibrium) representation is sufficient for accurate assessment or whether a structural form (general equilibrium) representation is required. Partial equilibrium approaches are the bioeconomic standard (for example see Smith, 2007) for small scale policies and welfare changes, while general equilibrium approaches are the public finance standard (for example see Carbone and Smith, 2008) for larger scale policies and welfare changes.

Partial equilibrium approaches are typically easy to implement as they hold all other economic activity constant (taking other prices and incomes as exogenous). They allow an uncluttered view of the economic activity directly affected by the acidification and a clear representation of optimal planning over long time horizons through the effect of environmental dynamics on choices. In addition they typically require few parameters. However they only provide a narrow viewpoint, they omit all other human adaptation and often omit a connection to welfare economics.

In contrast a general equilibrium representation allows the adaptations in the economic system to be represented. Prices and incomes are endogenous, there is an inclusion of producer and consumer behavior throughout an economic and allow a clear link to the principles of welfare economics. However these methods require numerous parameters, they are exceedingly hard to dynamically optimize, their broad viewpoint makes decomposing welfare effects impossible and can obscure the influence of environmental dynamics by economic responses.

Both methodologies have pros and cons, the question boiling down to a determination of the the appropriate balance. For the problem of ocean acidification this would tend to depends on the setting. For example, when considering the consequences on aquaculture a partial equilibrium approach may suffice, especially if the consequences are confined to the near shore and few other exploited (or non-market) populations. Regardless the lack of scientific research into this issue from an economic viewpoint is glaring. To say much more requires some hard scientific effort.

In conclusion, the point of my talk is that welfare measurement of materials damages has some well known characteristics but for this problem a lot remains unresolved and work remains. There is a high likelihood in my opinion that generating accurate assessments will be tricky and generalities seem to be lacking. A necessary first step is a a clear understanding of how production and consumption possibilities are affected by the problem in a consistent setting. While dose response relationships of environmental change from the natural sciences are key, but how much detail is necessary for a good understanding remains to be resolved in this context.

The implications from this brief review are obvious. If problems are convex or well behaved then aggregate representations of the natural science may be sufficient for good economic assessments. But if these problems have pervasive non-convexities then policy makers must expand the scope of their analysis for good economic assessments. Marginal assessments on their own may lead to trouble.

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Economic Impact of Climate Change and Ocean Acidification on Fisheries

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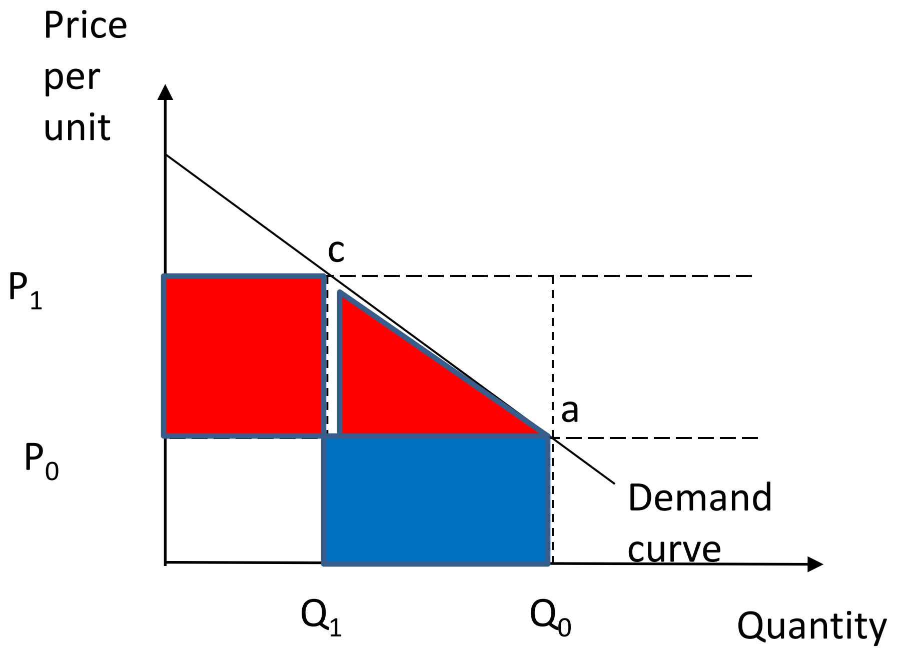
U.S. EPA/DOE Workshop, "Research on Climate Change Impacts and Associated Economic Damages", January 27-28, 2011, Washington D.C.

Ocean Acidification

- Past declines in ocean surface pH linked to mass extinction events
- Reduction in carbonate ion concentration
  - > reduction in calcium carbonate saturation
  - > impacts on marine calcifiers
  - >requires marine calcifying organisms to use more energy to form biogenic calcium carbonate
    - Hampered reef formation of corals, algaes
    - Hampered shell formation of oysters, clams and crabs

Economic consequences: S.R. Cooley and S.C. Doney. 2009. “Anticipating ocean acidification’s economic consequences for commercial fisheries.” *Environ. Res. Lett.*



•Calculated potential revenue losses from decreased mollusk harvests of 6%–25% from 2007 level were to occur in 2009, $75–187 million in direct revenue would be lost each year into the future, with a net NPV loss of $1.7–10 billion through 2060

•No direct connection between replacement costs and a useful welfare measure

Economic Consequences

- May disrupt provisioning of ecosystem services (ES)
- One of a class of “Materials Damages” problems studied in detail by Tom Crocker 25 years ago
- Human welfare is dependent on biological systems (material environment) that provide critical inputs to human activity
- Damages or improvements in material environment implies welfare changes

Assessment of Materials Damage Requires:

1. Characterization of the differential changes across time and space that environmental change causes in production and consumption opportunities
2. Determination of the responses of input and output market prices to these changes
3. Identification of the adaptations that affected agents can make to minimize losses or maximize gains from changes in opportunities and prices

Economic Effects:

- Perturbations in provisioning of ES change producers production possibilities
- Degradation may reduce production possibilities
- Perturbations in provisioning of ES may change costs facing households directly or indirectly (access costs)
- Objective functions and behavior towards new sets of production and consumption possibilities remains the same
- First key question: how do to bring these changes in possibilities into economic analysis?

Bringing Environmental Changes into the Economic Assessment

Reduced Form Representation:
- easy to fit to limited data
- gives good view of general processes

BUT
- aggregation can cause errors in economic estimates

(Kopp and Smith, 1980 BJE)

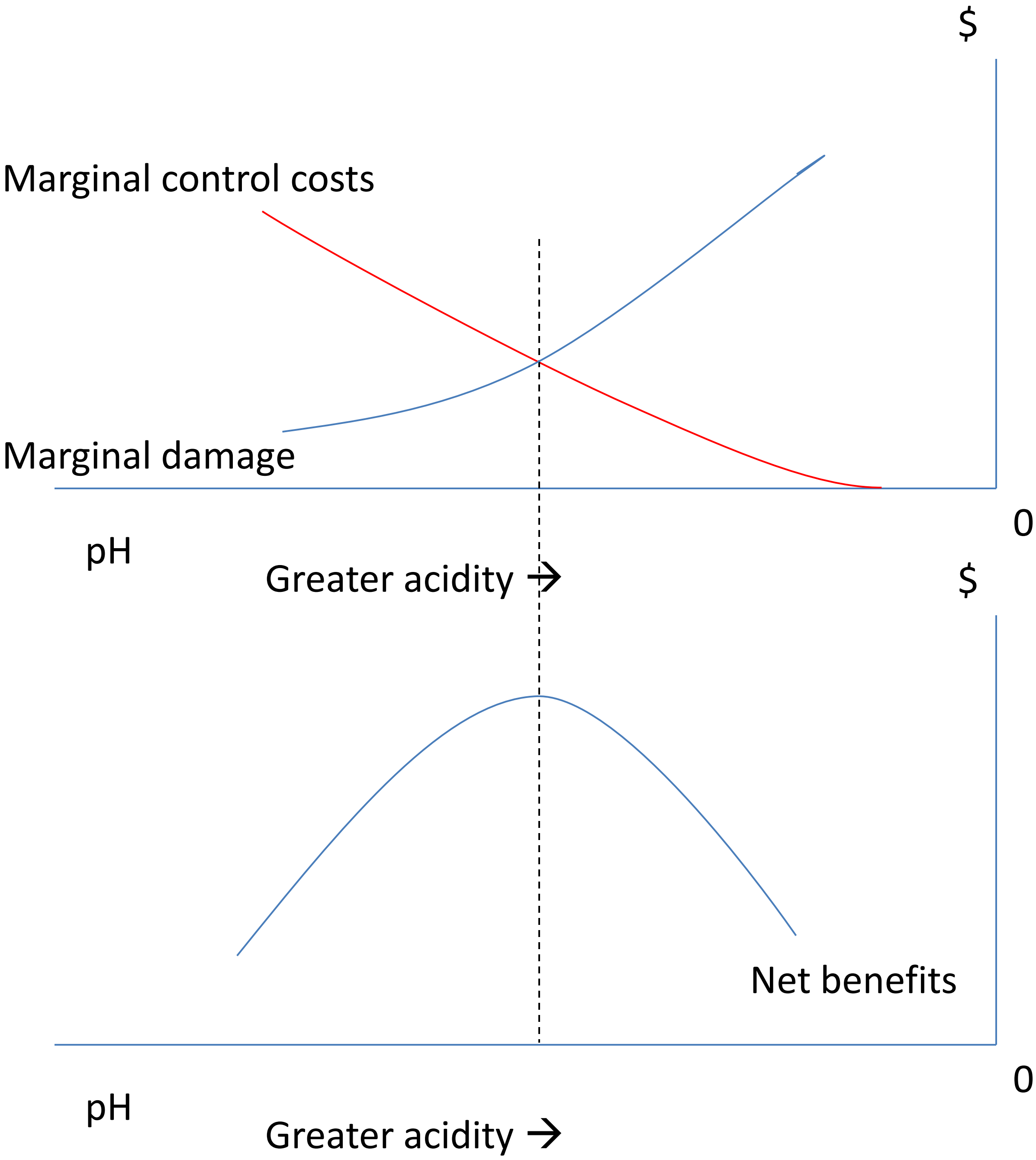
Structural Representation:
- can represent critical details explicitly
- capture within system adaptations

BUT
- contribution of additional natural science information declines rapidly

(Adams, Crocker and Katz, 1984 RESTAT)

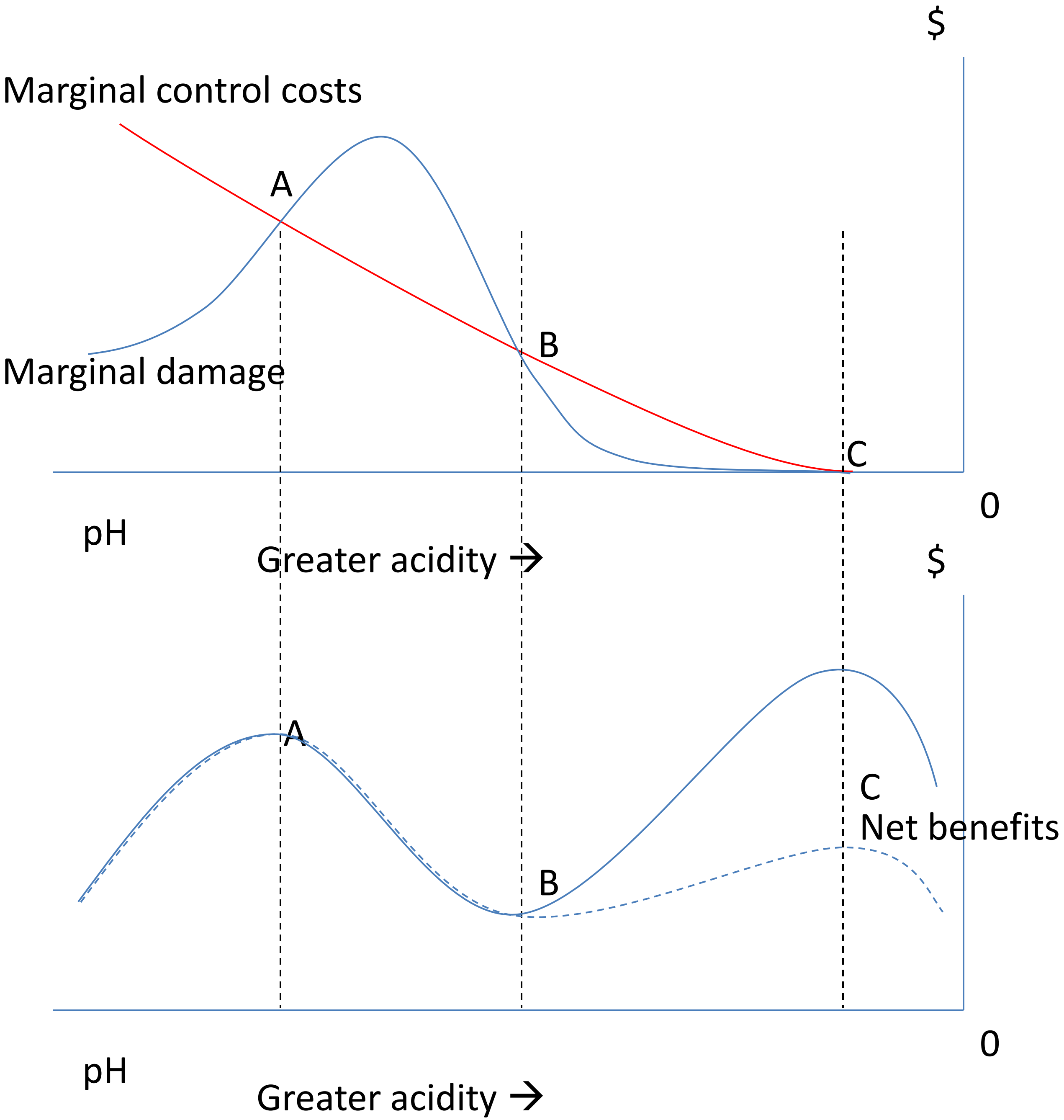
Appropriate Balance?
- in one dimension balance depends on potential of non-convexities
- If problems are convex reduced form representation likely sufficient
- If there are pervasive non-convexities high level of abstraction may lead to trouble – need to know the entire possibilities surface

Standard setting



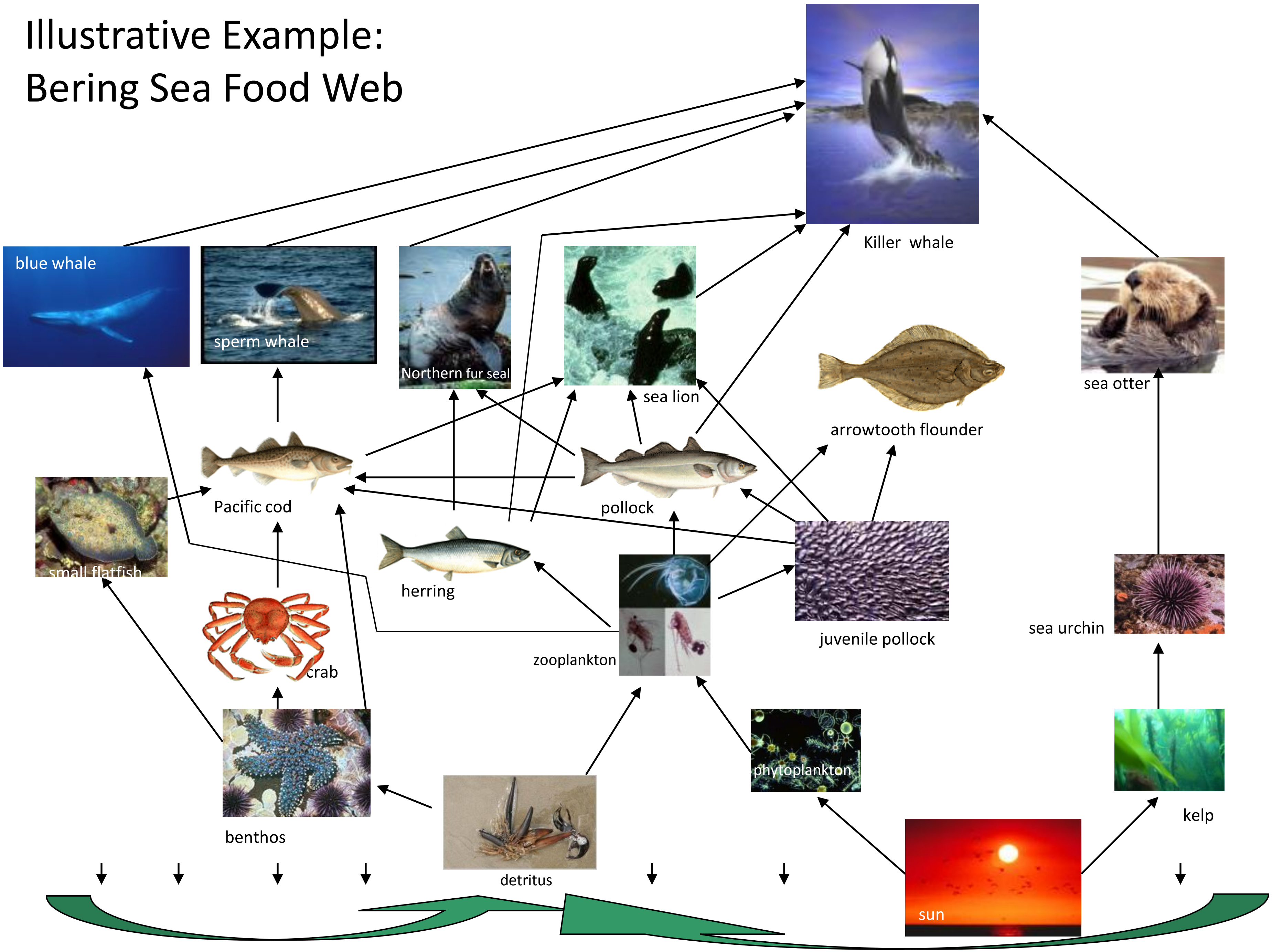
- single equilibrium
- marginal comparisons alone sufficient to signal how to max social net benefits

Non-convexities



- multiple equilibria
- natural and economic adjustments not as clear – requires an expansion of the scope of analysis
- marginal comparisons alone insufficient to signal how to max social net benefits
- need know the entire surface (across environmental change) to locate global optimum and understand how the marginal damages change

Illustrative Example: Bering Sea Food Web



GEEM: Developed to track ecological adjustment

1) fitness net energy

$$R_i = \sum_{j=1}^{i-1} [e_j - e_{ij}] x_{ij} - \sum_{k=i+1}^{m} e_i [1 + t_i e_{ki}] y_{ik} (\sum_{j=1}^{i-1} x_{ij}) - f^i (\sum_{j=1}^{i-1} x_{ij}) - \beta_i$$

2) biomass transfers (similar to market clearing)

$$n_i x_{ij}(\boldsymbol{e}_i) \leq n_j y_{ji}(\boldsymbol{x}_j(\boldsymbol{e}_j))$$

3) population updating

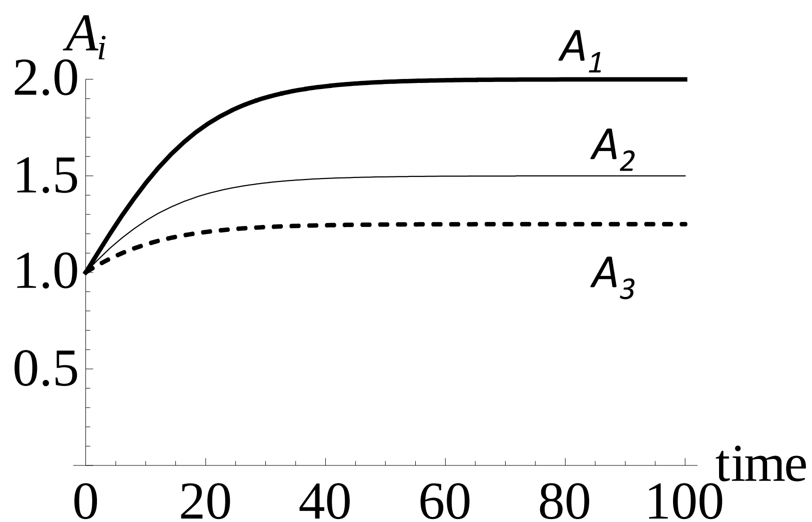
$$n_i^{t+1} = n_i^t + n_i^t \frac{1}{s_i} [\frac{R_i(\cdot) + v_i}{v_i^{ss}} - 1]$$

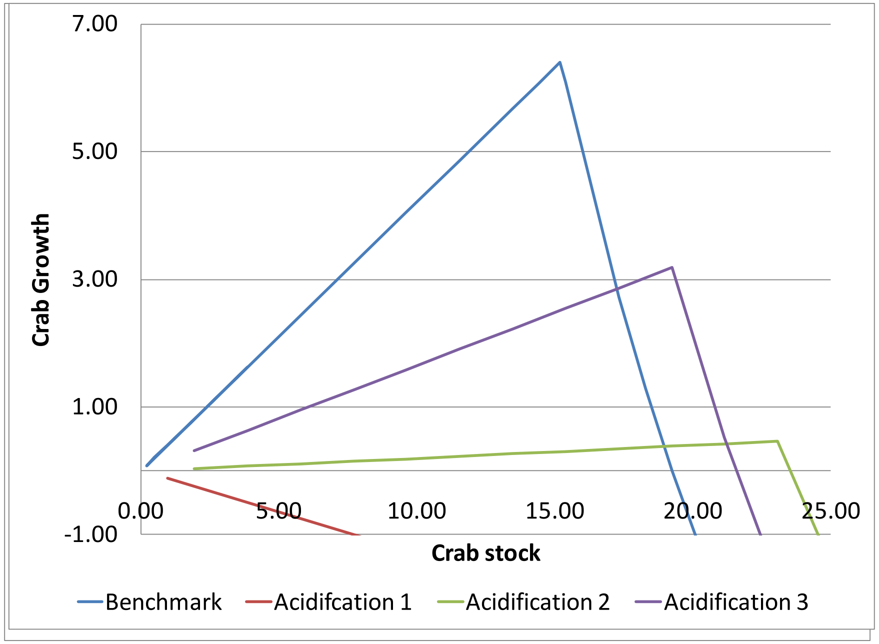
Acidification

Ad Hoc: Acidification increases variable respiration requirements of crabs for any level of biomass consumption

$$f_{crab}(.) = A_i\, \alpha_{crab} x^2_{crab,benth}$$

$$A_i = \frac{a_i}{b_i + e^{-.1t}} \quad i = \{1,2,3\}$$




7.00
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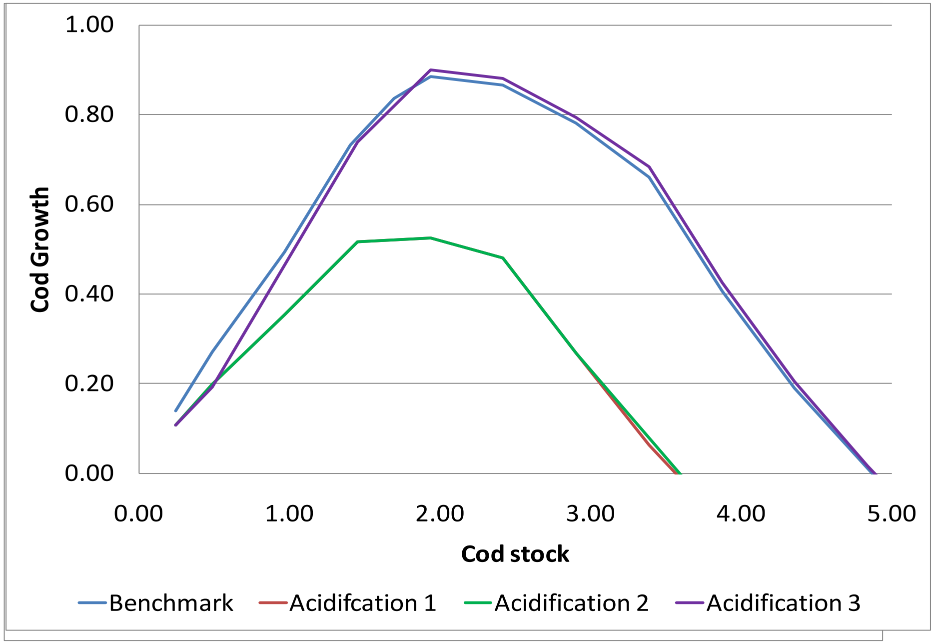
Acidification 3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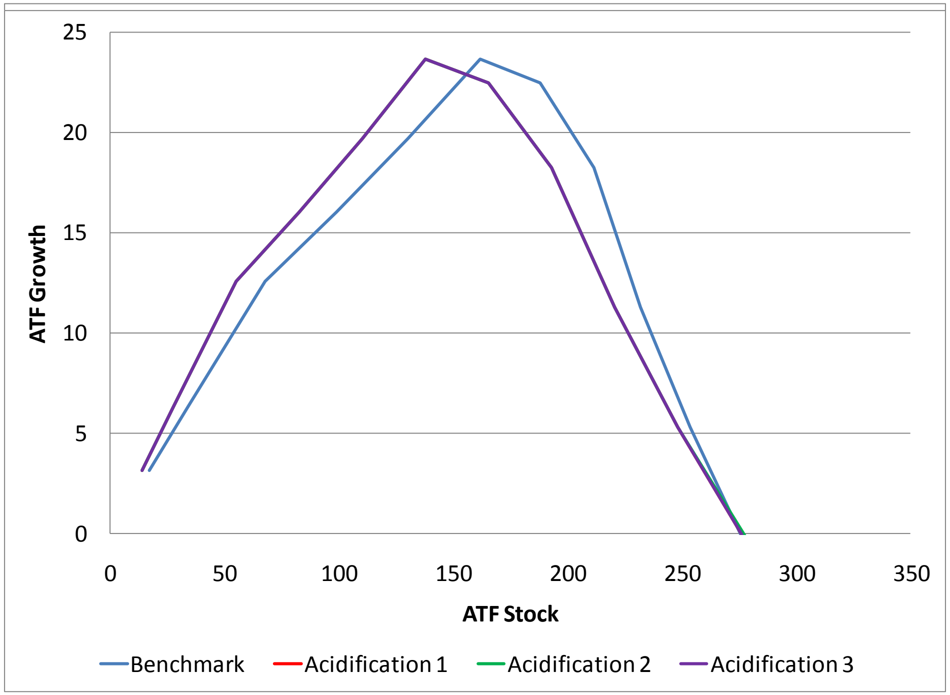
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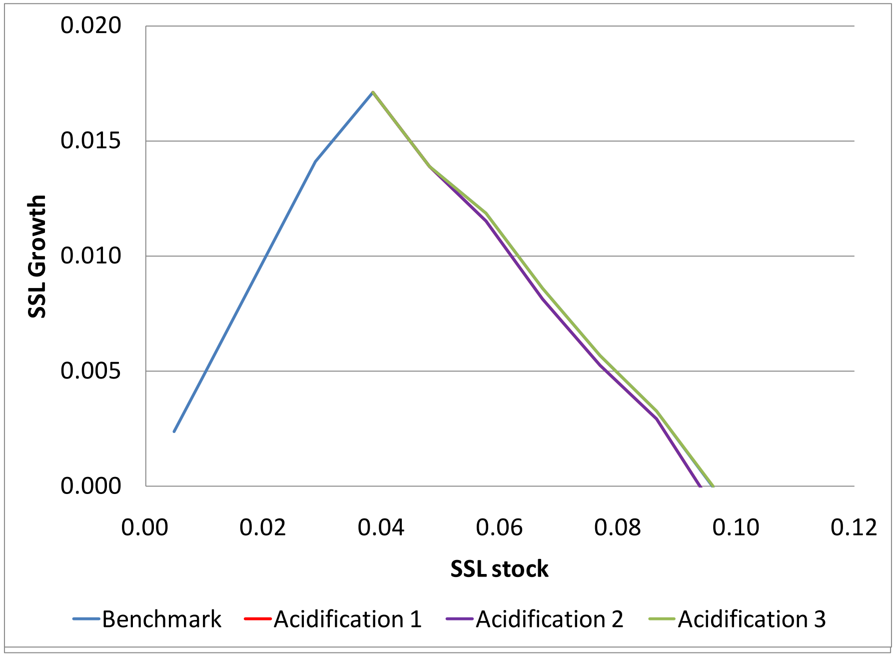
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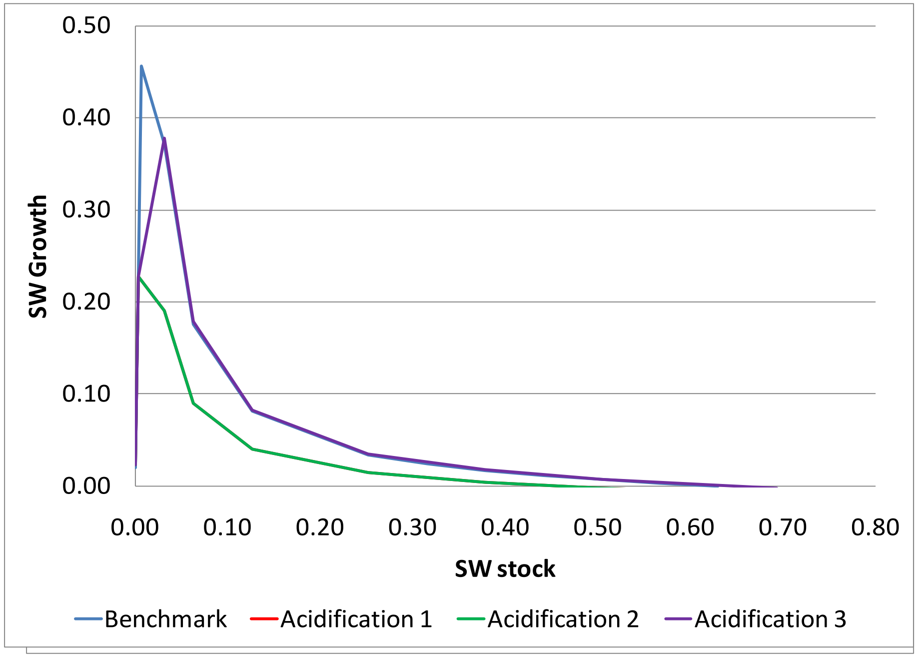
Acidification 3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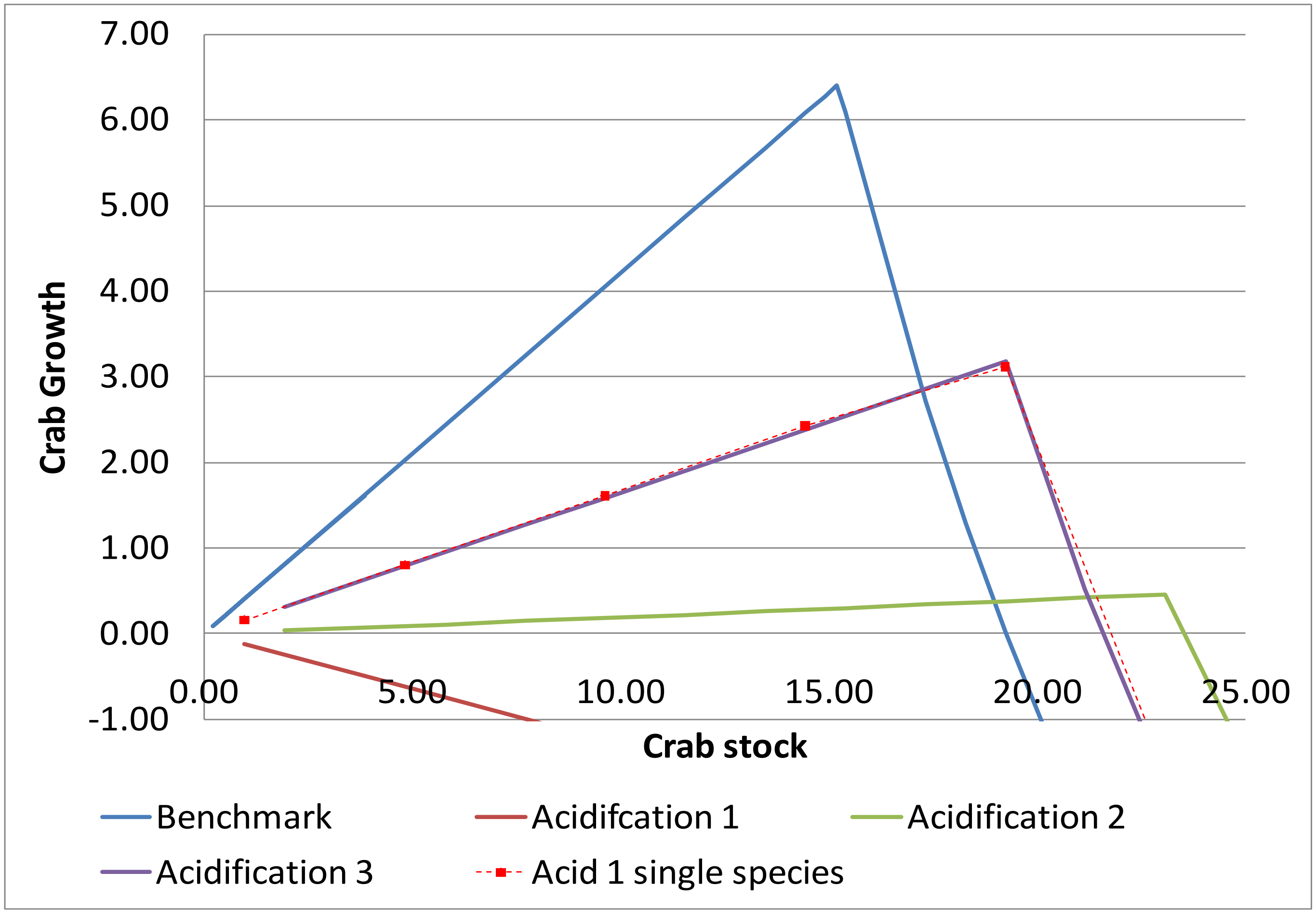
SW stock
Benchmark
Acidification 1
Acidification 2
Acidification 3

Implications:

- Consequences reverberate across system in varying degrees and magnitudes
- Seems to be a potential for non-convexities
  - Acidification a negative shock to crab optimization problem yet can see higher stocks (although less surplus growth)
  - Changes not always monotonic
  - Problems with reduced form aggregations

Representation of Environmental Changes:

Reduced Form Representation v's Structural Representation



Point:

- Bioeconomic harvests of fish and crab likely affected to varying degrees and magnitudes depending on location in food web
- Non-harvested stocks may or may not have cascading effects depending on location in foodweb
- To assess tradeoffs have to be able to access changes in flows and stocks simultaneously

Evaluating Environmental Changes: Do changes in relative prices matter?

Reduced Form / Partial Equilibrium Representation:

- other prices and incomes exogenous
- allows clear representation of optimal planning over long time horizons
- allows clear focus on effect of environmental dynamics on choices
- requires few parameters

BUT

- narrow viewpoint, omits all other adaptation
- typically omits a connection to welfare economics
- not clear how specific scientific information be included into lumped parameters

Structural / General Equilibrium Representation:

- prices and incomes endogenous
- system wide adaptation
- clear link to principles of welfare economics and inclusion of producer and consumer behavior
- Enough detail to include specific scientific information

BUT

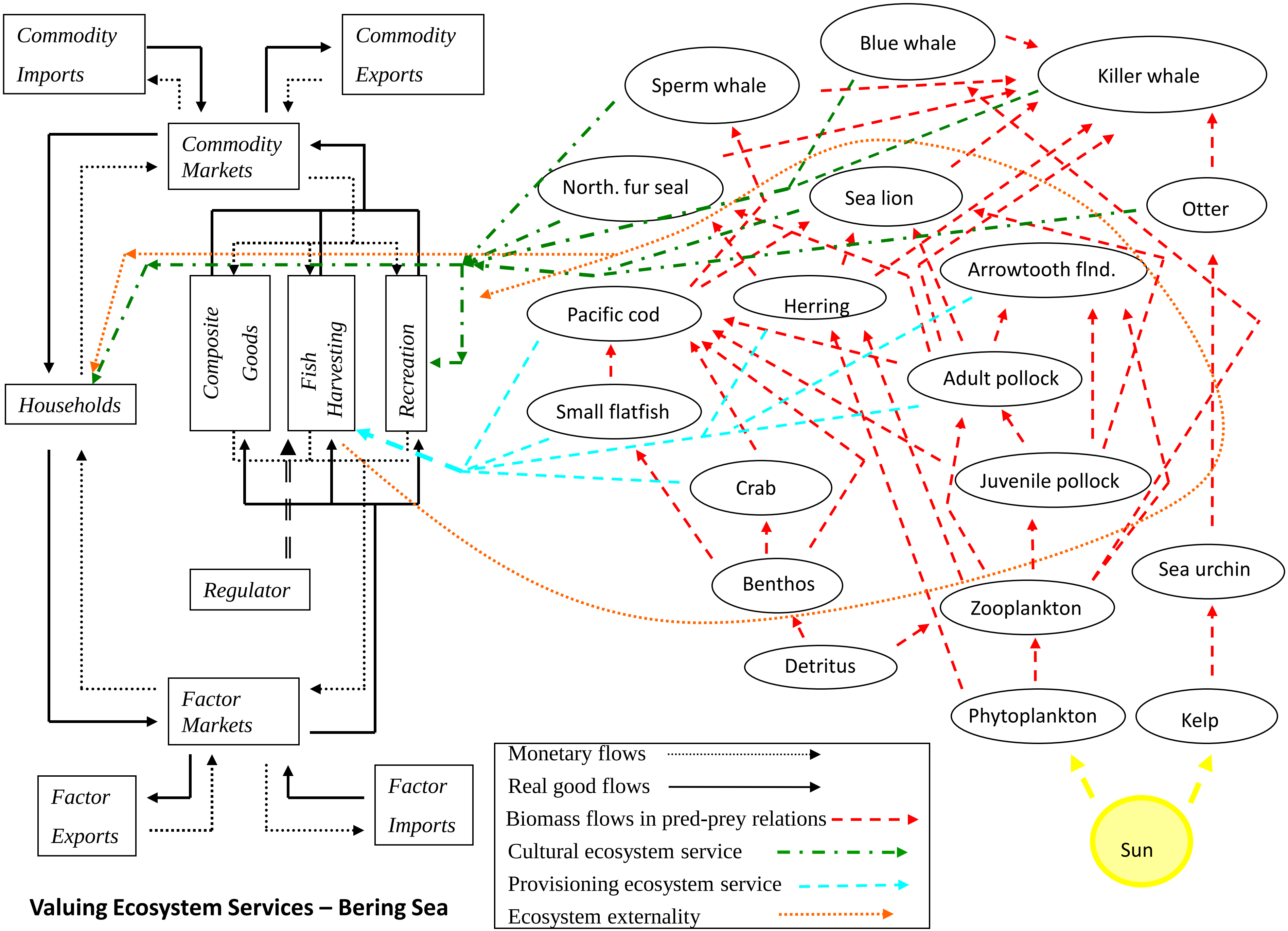
- requires numerous parameters
- hard to dynamically optimize
- broad viewpoint makes decomposing effects tricky
- influence of environmental dynamics obscured by economic responses

What is the Appropriate Balance????

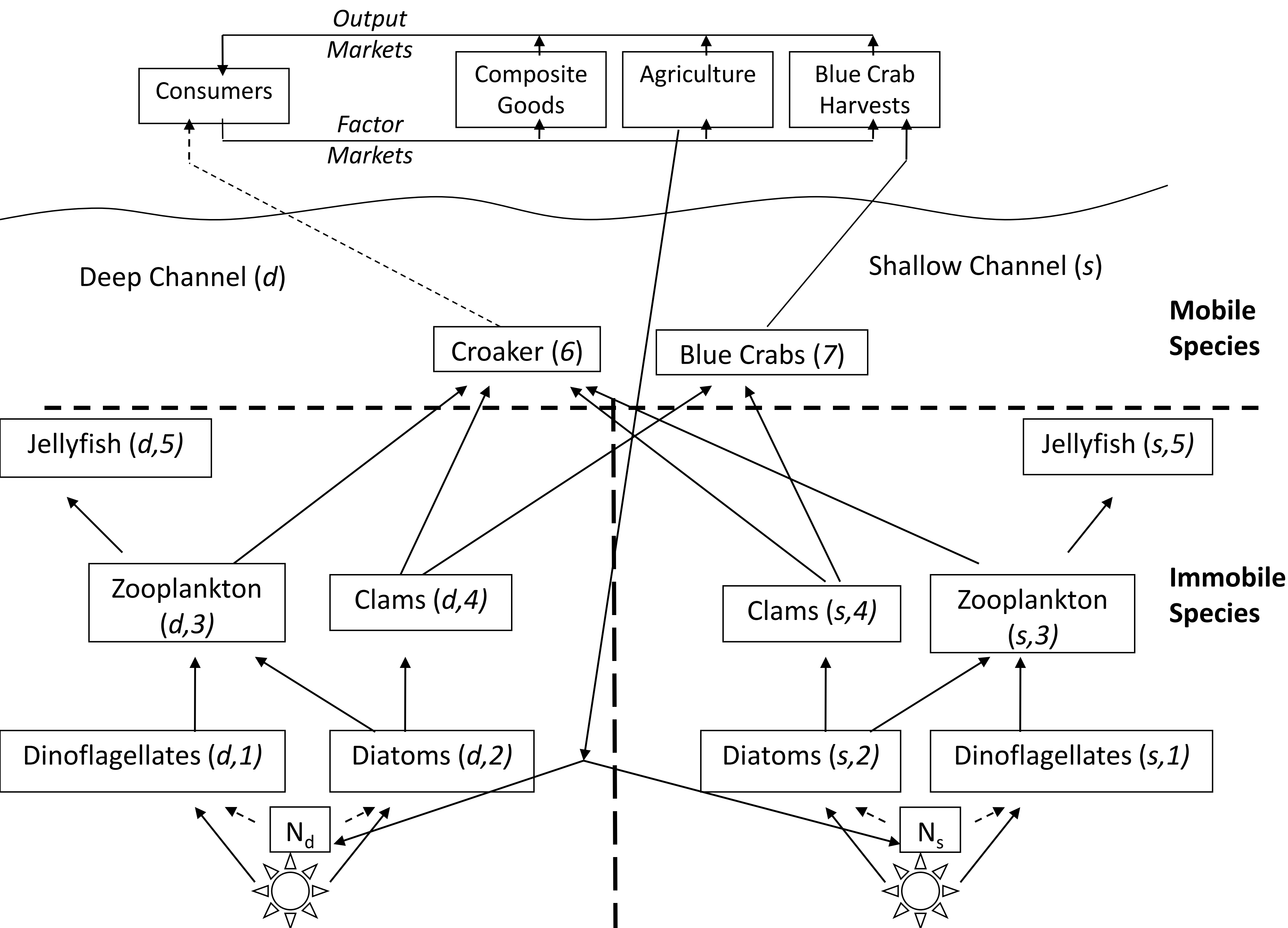
Conclusions

Point: Welfare measurement of materials damages has some well known characteristics but for this problem a lot remains unresolved and work remains

1. Accurate assessments tricky, generalities seem to be lacking
2. Need a clear understanding of how production and consumption possibilities are affected by the problem in a consistent setting
   – dose response relationships of environmental change from the natural sciences are key, but how much detail is necessary for a good understanding remains to be resolved
3. If problems are convex or well behaved then aggregate representations of the natural science may be sufficient for good economic assessments
4. If problems have pervasive non-convexities then policy makers must expand the scope of their analysis for good economic assessments – marginal assessments on their own may lead to trouble (G. Brown, REE, forthcoming)



Valuing Ecosystem Services – Bering Sea



Output Markets
Consumers
Composite Goods
Agriculture
Blue Crab Harvests
Factor Markets
Deep Channel (*d*)
Shallow Channel (*s*)
Mobile Species
Croaker (*6*)
Blue Crabs (*7*)
Jellyfish (*d,5*)
Jellyfish (*s,5*)
Immobile Species
Zooplankton (*d,3*)
Clams (*d,4*)
Clams (*s,4*)
Zooplankton (*s,3*)
Dinoflagellates (*d,1*)
Diatoms (*d,2*)
Diatoms (*s,2*)
Dinoflagellates (*s,1*)
N_d
N_s

U.S. EPA/DOE Workshop, "Research on Climate Change Impacts and Associated Economic Damages," January 27-28, 2011, Washington D.C.

Abstract: Nonmarket valuation of climate change and ocean acidification impacts to marine resources

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December 22, 2010

Introduction

The purpose of this abstract is to describe existing methods of estimating the economic values for avoiding the climate change impacts to marine resources. In the first section I describe the available methods. In the next section I review the literature focused on recreation values associated with climate change. In the third section I consider a conceptual model for valuing climate change impacts to marine resources. In the fourth section I consider future research needs.

Methods

Estimating the nonmarket values of climate change impacts to marine resources first requires consideration of the type of impacts. Market values are the changes in outputs and inputs associated with a resource reallocation and are valued with market prices. Nonmarket values are those that accrue above and beyond market values and are variously called consumer surplus, compensating surplus, equivalent surplus, willingness to pay and willingness to accept. The total economic value is the sum of all nonmarket values.

Estimation of the total economic value for marine resources is complex. Consider coral reefs which can provide recreation and tourism values, amenity values, fishery habitat values and biodiversity values (Figure 1). The main categories of nonmarket values include direct use values, indirect use values and nonuse values. Direct use values are those that arise from on-site enjoyment of a natural resource. Direct use values that are generated by marine resources are primarily recreational and tourism values. In Figure 1, individuals can enjoy recreational diving on the coral reef ecosystem and gain direct use values. Indirect use values are those that are enjoyed on-site as a by-product of coral reefs. For example, fish stocks are enhanced by coral reef protection and anglers enjoy coral reef protection indirectly through improved catch rates. Nonuse values are those values that arise without on-site enjoyment. Nonuse values may be motivated by altruism, bequests or an environmental ethic.

Both revealed and stated preference methods can be used to estimate direct and indirect nonmarket use values. The most advantageous revealed preference nonmarket valuation method for outdoor recreational modeling is the travel cost method. The travel cost method exploits the empirical relationship between outdoor recreation trips and site selection and the travel cost required to reach recreation sites. The most basic finding is that the further the distance the less likely the recreation site will be selected and the fewer the number of trips.

Stated preference methods include the contingent behavior, contingent valuation and attribute-based choice experiment (i.e., conjoint analysis) methods. The contingent valuation method could be used by asking survey respondents for their willingness to pay to prevent climate change to recreation resources. The contingent behavior method could be used by asking survey respondents for hypothetical changes in visitation behavior (i.e., trips) with changes in climate related variables. Attribute-based choice experiments can be used by asking survey respondents about changes in visitation behavior (i.e., site selection) with changes in climate related variables.

Both revealed and stated preference methods have limitations when valuing the impacts of long term climate change. Revealed preference methods are constrained by current spatial variations in temperature and other measures of climate change impacts. Forecasts of the impacts of temperature change beyond current experience are possible but the range and types of behavior change are constrained by the model and existing behaviors. Stated preference methods are limited in that the measured behavior is hypothetical and subject to potential biases. One approach for resolving these weaknesses is the combination and joint estimation of revealed and stated preference data. Joint estimation allows the behavior change to range beyond historical experience with the stated preference data while grounding the hypothetical data in revealed preferences.

Stated preference methods must be used to estimate nonuse values. The contingent valuation method can be used to ask survey respondents about their willingness to pay for climate change policy that would change the characteristics of marine resources. One problem with the contingent valuation method in this context is that it is most effectively employed to estimate total economic values. Willingness to pay for climate change policy could also capture marine resource values, coastal values, terrestrial values and others. Attribute-based choice experiments can also be used to estimate nonuse values. Respondents are typically led through a series of policy choices with varying characteristics of the policy. In the case of coral reef valuation, these characteristics could include changes in the ecosystem, fish stocks and other impacts with and without opportunities for recreation. Simulation methods can then be used to estimate nonuse values.

Literature on Outdoor Recreation and Climate Change

Past research on the impact of climate change on outdoor recreational activities is relatively sparse. Early studies found that precipitation and temperature affects beach recreation activities (McConnell 1977, Silberman and Klock 1988). Mendelsohn and Markowsi (1999) considered the effects of changes in temperature and precipitation on a wide range of outdoor recreational activities using state-level aggregate demand functions. Considering a range of climate scenarios, the authors found that increased temperature and precipitation increase the aggregate economic value of some activities and decreases the aggregate economic value of others. Loomis and Crespi (1999) took an approach similar to Mendelsohn and Markowsi (1999) but used microdata. They considered the effects of temperature, precipitation and other climate change impacts (e.g., beach length, wetland acres) on a wide range of outdoor recreational activities. Overall, they found that climate change is likely to have positive impacts on the aggregate economic value of outdoor recreation activities.

Several studies have focused on more narrow regions and outdoor recreational activities. Pendleton and Mendelsohn (1998) related the effects of temperature and precipitation to catch rates for trout and pan fish in the northeastern United States. Climate change is expected to decrease trout catch rates and increase pan fish catch rates. Using microdata, the authors found that fish catch rates influence fishing site location choice. Combining the effects of climate change on catch rates the authors found that climate change would benefit freshwater fishing in the northeastern United States. Ahn et al. (2000) focused on trout fishing in the Southern Appalachian Mountain region of North Carolina. Using methods similar to Pendleton and Mendelsohn (1998) the authors found contrasting results. Based on their results climate change would reduce the economic value of trout fishing in this region. The contrast may be due to a lack of species-substitution possibilities. More recently, Englin and Moeltner (2004) estimated weekly skiing and snowboarding trip demand models and integrate weekly weather conditions as a factor affecting demand. They find that temperature and precipitation affect the number of skiing and snowboarding days in expected ways.

All of the previous studies used revealed preference methods. In contrast, Richardson and Loomis (2004) employed a stated preference approach to estimate the impacts of climate change on economic value for recreation at Rocky Mountain National Park. Richardson and Loomis' hypothetical scenario explicitly considered the direct effects of climate, temperature and precipitation, and the indirect effects of temperature and precipitation on other environmental factors such as vegetation composition and wildlife populations. They found that climate change would have positive impacts on visitation at Rocky Mountain National Park.

A Conceptual Model

There are a number of relationships that need to be modeled to estimate a marine rsources damage function (Figure 2).[1] First, a simple model of the effect of carbon dioxide emissions on ocean acidification is needed. The simple model should be able to abstract away from the biophysical complexities and allow focus on the endpoints that are important for anthropogenic valuation. For example, a description of how carbon dioxide emissions affect seawater variables and other weather-related variables important to recreation (e.g., ambient temperature, precipitation) is needed. Considering the example of coral reef ecosystems, let this relationship be expressed as equations (1) and (2):

(1) $S = f(CO2)$
(2) $W = f(CO2)$

where *S* represents seawater variables (e.g., temperature, chemistry), *W* represents weather-related climate change variables (e.g., ambient temperature, precipitation) and *CO2* represents carbon dioxide. In Figure 2 this relationship is represented by the arrows labeled (1) and (2).

[1] Note that this model is what is understood by an economist with no training in climate science.

Next, a biophysical description of the effect of seawater and other climate variables on coral reef ecosystems and fish stocks (e.g., range shifts, habitat loss, and prey availability) is needed.

(3) $CR = f(S, W)$
(4) $FS = f(S, W, CR)$

where *CR* is coral reef ecosystem and *FS* is fish stocks. In Figure 2 these relationships are represented by the arrows labeled (3) and (4). Note that fish stocks are affected by seawater variables and other climate variables directly and indirectly through coral reef ecosystems.

Next, behavioral models could be estimated with revealed preference methods such as the travel cost method:

(5) $RD = f(p, y, CR)$
(6) $RF = f(p, y, FS)$

where *RD* is recreational diving, *RF* is recreational fishing, *p* is the access cost of each activity (e.g., travel cost) and *y* is income. In Figure 2 these are illustrated by the arrows labeled (5) and (6). The link between carbon dioxide emissions and recreational behavior can be found by substituting equations (1) and (2) into (3) and substituting equations (1), (2) and (3) into equation (4). Then equation (3) would be substituted into equation (5) and equation (4) would be substituted into equation (6). The reduced form behavioral models are:

(5') $RD = f\big(p, y, S, W, CR(S, W)\big)$
(6') $RF = f(p, y, S, W, FS(S, W, CR))$

To estimate recreational impacts from climate on marine recreational behavior in a revealed preference study, one would follow the methods employed in previous studies. Considering the conceptual framework developed by Shaw and Loomis (2008), one would estimate the relationship between the direct effects of climate change (e.g., temperature, precipitation, climate variability), the indirect effects (e.g., fish stocks and composition) and the effects on outdoor recreational behavior and economic value. Data with spatial variation in the climate change variables is required.

In particular, consider the random utility model version of the revealed preference travel cost method. In this model, it is assumed that individuals choose recreation sites based on tradeoffs among trip costs and site characteristics (e.g., temperature, precipitation, catch rates). If anglers make fishing site selections based on these characteristics, then the existing relationship between site characteristics and fishing site selection can be used to simulate the impact of climate change. This model could then be linked to models of visitation frequency to estimate the aggregate impacts of climate change on marine recreation behavior. Stated preference recreation scenarios can be designed to elicit hypothetical behavior data to supplement the revealed preference data in a joint estimation framework.

The simple biophysical descriptions represented by equations (1), (2), (3) and (4) could be used to design stated preference recreation scenarios for estimation of use values and policy scenarios for estimation of nonuse values. First, nonuse values must be conceptually defined. Economists use the utility function to conceptualize the relationship between consumption and welfare (i.e., happiness). Considering the example above:

(7) $U = U(X, RD, RF, CR, FS, U^a U^b)$

where U is the utility of an individual, X represents market goods, U^a represents the utility of individual a (i.e., altruism) and U^b represents the utility of individual b (i.e., bequests to future generations). Changes in *RD* and *RF* that affect utility represent behavior that generates use values. Changes in *CR* and *FS* generate nonuse values motivated by an environmental ethic. Changes in U^a and U^b generate nonuse values motived by altruism and bequests to future generations. These relationships are represented by the arrows labeled (7) in Figure 2.

Substitution of equation (7) for individuals *a* and *b* leads to a reduced form utility function which can be maximized subject to a budget constraint to find the indirect utility function:

(8) $v = v(p, y, CR, FS)$

Use and nonuse values can be conceptually defined using equation (8). The total economic value of a change in coral reef ecosystems from the baseline level to a degraded state (*CR*', *FS*') is:

(9) $v(p, y - TEV, CR, FS) = v(p, y, CR', FS')$

where TEV is the total economic value, the amount of income that must be taken from the individual in order to maintain utility at a level equal to that with full income but a degraded environment. Total economic value is the sum of use value and nonuse value, TEV = UV + NUV, where nonuse value is:

(10) $v(p^*, y - NUV, CR, FS) = v(p^*, y, CR', FS')$

where *p** is the price at which the quantity of recreation demanded is equal to zero. The residual difference between TEV and NUV is equal to the sum of the use values from equations (5') and (6'). Contingent valuation or attribute-based choice experiment scenarios can be described to convey the information included in equations (1) – (10) and obtain estimates of total economic values and nonuse values for the impacts of climate change on marine resources. Joint estimation with recreation demand functions (5') and (6') can be used to decompose total economic value into use value and nonuse value and further calibrate the model.

Future Research

Future research must be conducted to determine how the biophysical models could be integrated with the economic models. To my knowledge there are no good examples in the literature.[2] Important gaps and uncertainties in our knowledge regarding the economic impact of changes in fisheries and coral reef ecosystems due to climate change are the lack of empirical relationships described above. One of the next steps to improving how nonmarket impacts to marine ecosystem service impacts are handled in an integrated assessment modeling framework is to gather the necessary revealed preference and stated preference data and estimate the relationships described above. The accuracy of transfers of these damage functions across regions and over long periods of time is an open question, requiring validity studies. Research examining these relationships would be most fruitful. In the interim, investigation of benefit transfer methods with existing estimates of coral reef recreation and recreational fishing values would allow preliminary estimation of these damage functions.

[2] Note that I still have a stack of papers to read and have not yet exhausted my literature search abilities.

Figure 1. Nonmarket Economic Values

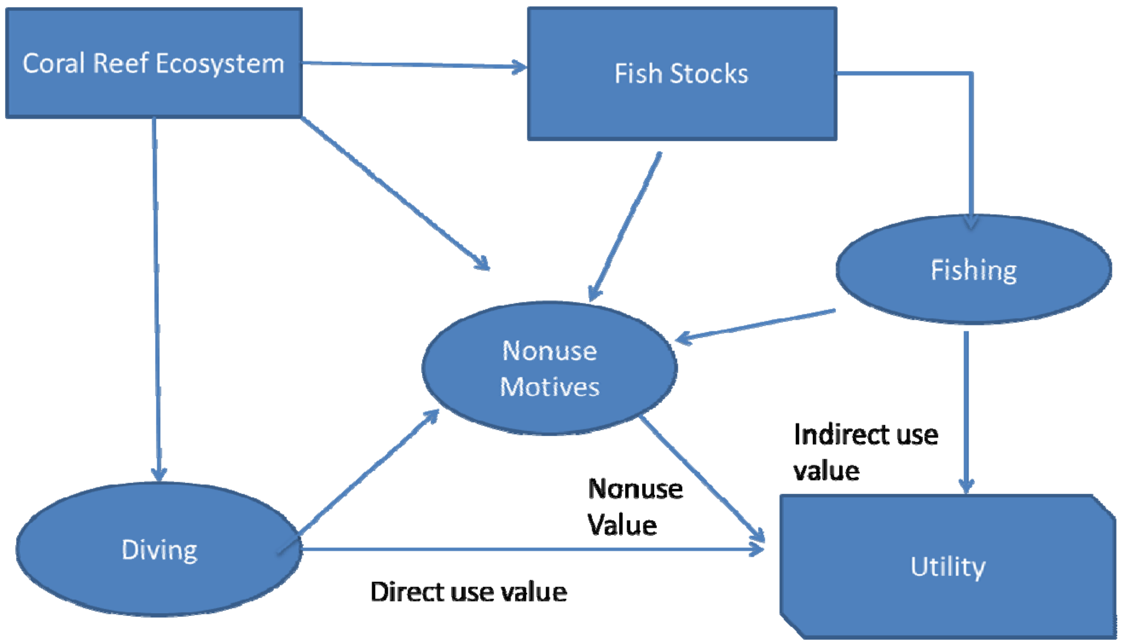
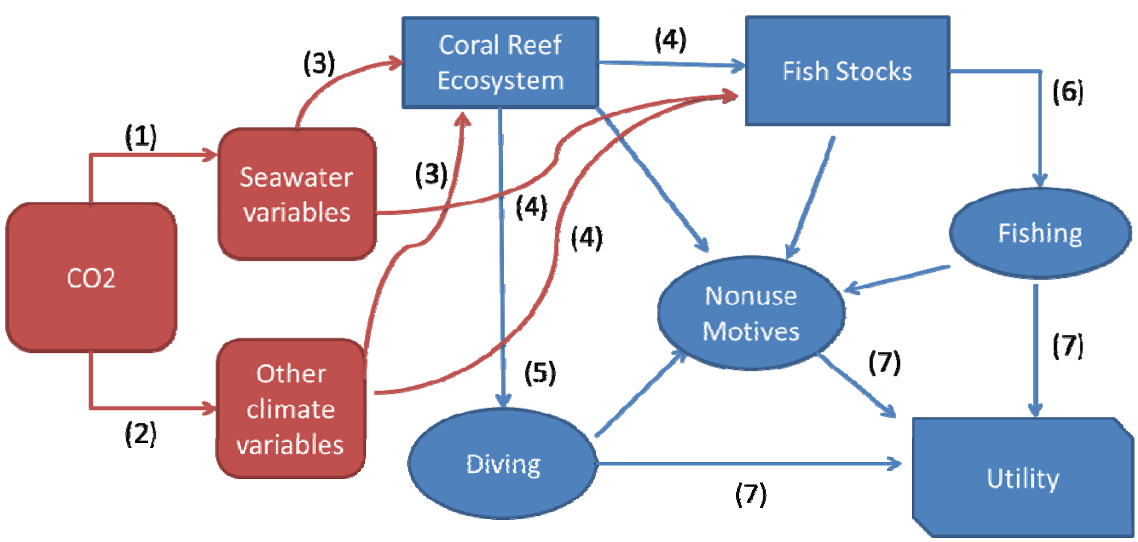


Figure 2. Climate Change and Nonmarket Economic Values



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Nonmarket Valuation of Climate Change and Ocean Acidification Impacts to Marine Resources

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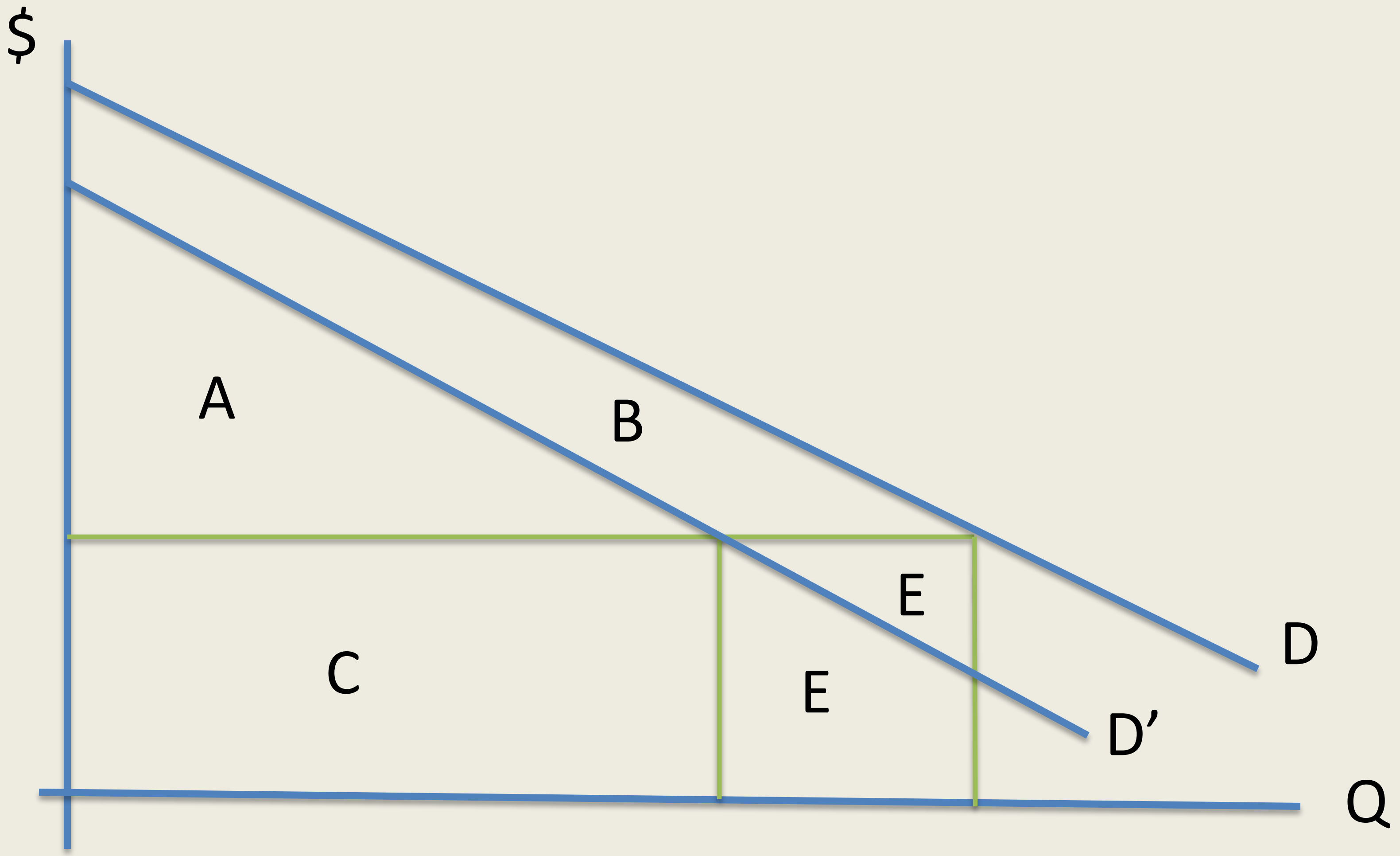
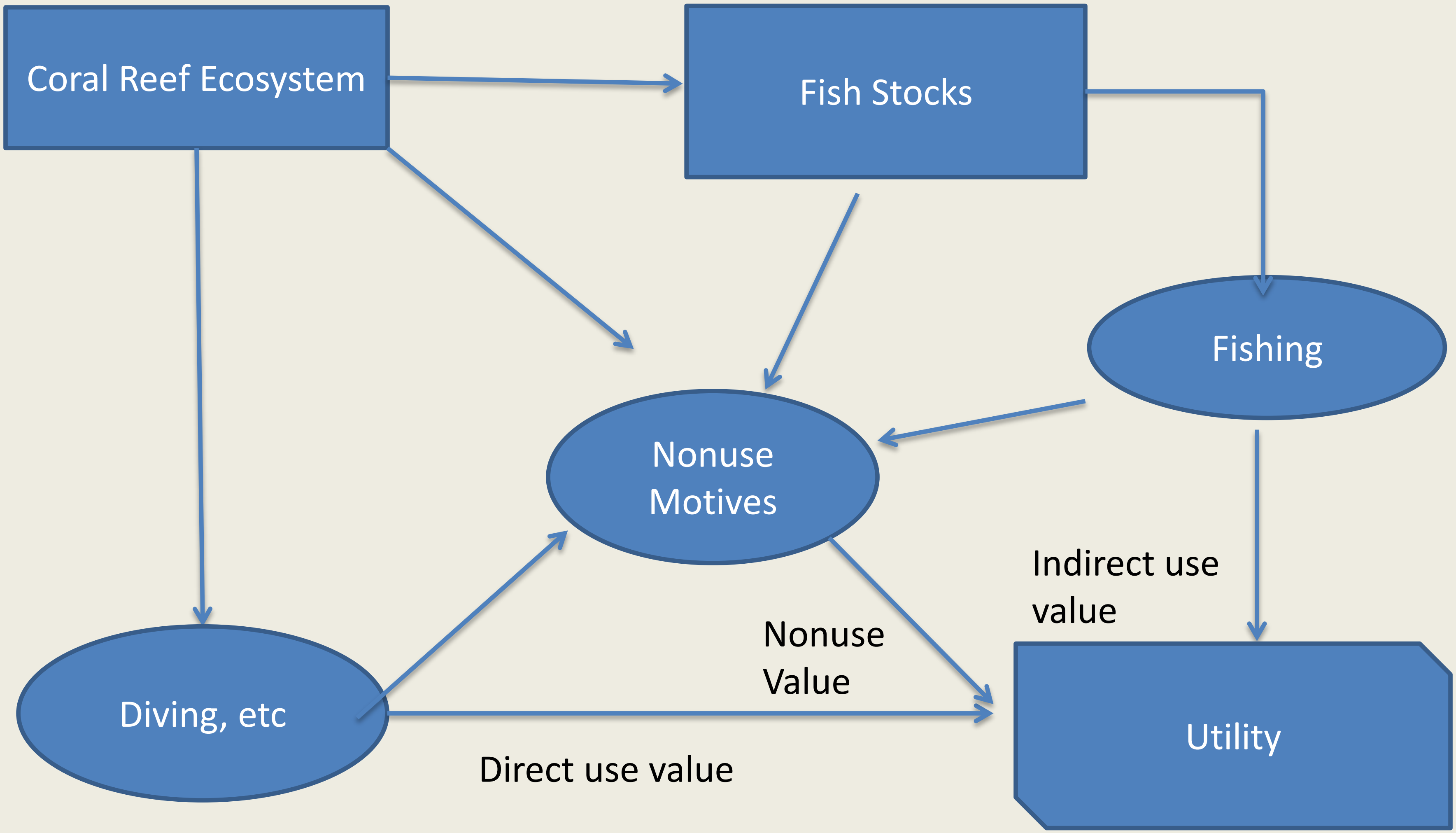
Nonmarket Values



Nonmarket Values for Coral Reefs



Use values

- Willingness to pay to avoid climate change to marine resources due to use of these resources on-site
- Direct use
  - Diving
  - Snorkeling
  - Viewing
- Indirect use
  - Fishing (coral reef habitat and nursery functions)

Nonuse (aka, passive use) values

- Willingness to pay to avoid climate change to marine resources without the intent to use these resources on-site
- Motives
  - Altruism (WTP today for Δq today)
  - Ecological ethic (WTP today for Δq today)
  - Bequests (WTP today for Δq in the future)

Measurement of Total Economic Value

	Types of Value	
Valuation Methods	Use	Nonuse
Revealed Preference	**Yes**	**No**
Stated Preference	**Yes**	**Yes**

Revealed Preference Methods

- Types
  - – Hedonic price method
    - Property values
  - – Averting behavior method
    - Health values
  - – Travel cost method
    - Recreation values
      - – Single site TCM
      - – Multiple site RUM
  - – NFI, PF, GR (generally not appropriate)

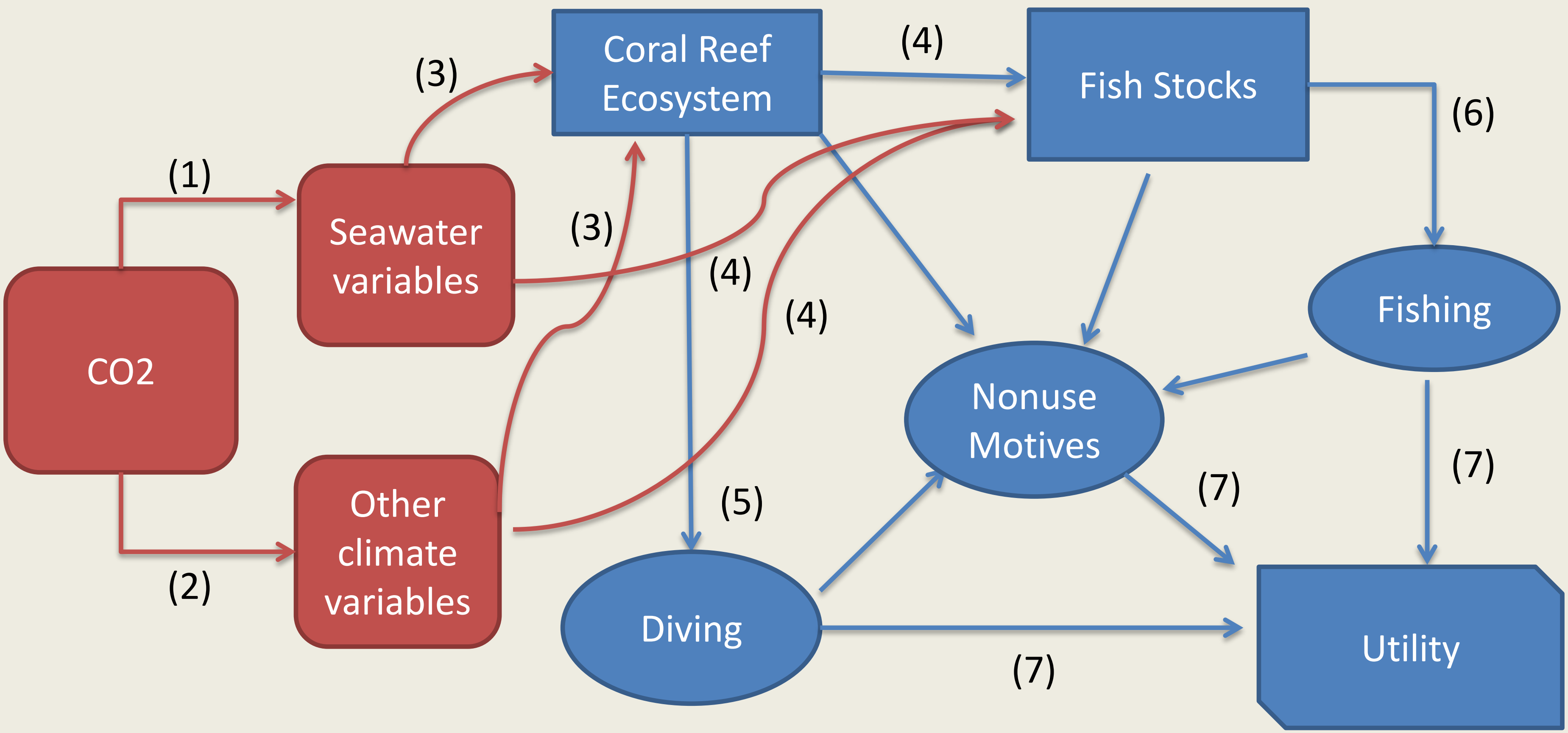
Stated Preference Methods

- Types
  - Contingent valuation
    - Used to estimate UV, NUV and TEV
    - difficult to avoid double counting in the case of climate change
    - WTP to climate change policy = bequest values
  - Choice experiments
    - Similar values as CVM Use to estimate UV, NUV and TEV
    - can be used to separate marine values from total values of climate change policy
  - Contingent behavior
    - Used to estimate recreation and other UVs

RP-SP Methods

- Problems with both RP and SP Methods
- Joint estimation of RP-SP data can mitigate some of these problems
- TCM/RUM with SP methods is used to estimate use and nonuse values

Climate Change and Nonmarket Values



Literature

- RP: Spatial variation in climate variables
  - Mendelsohn and Markowsi, 1999
  - Loomis and Crespi, 1999
  - Ahn, et al., 2000
  - Pendleton and Mendelsohn, 1998
- RP: Temporal variation in climate variables
  - Englin and Moeltner, 2004
  - Carter and Letson, 2009
- SP: Richardson and Loomis, 2004

A reduced form damage function

- Data
  - NSRE (1990, 2000)
  - NSFHWAR (every 5 years)
- Recreation Days = f(X; temp, precip, etc)

Saltwater Fishing Participation

Linear probability model				
Variable	Estimate	t-value	3F	7F
Intercept	1.9467	27.42		
income	-0.0009	-9.45		
white	-0.0379	-4.20		
male	-0.1035	-15.42		
age	0.0013	5.56		
educ	0.0046	3.11		
hhnum	-0.0087	-3.13		
under6	-0.0002	-0.03		
metro	-0.0315	-3.82		
jantemp	-0.0022	-5.90	-0.00666	-0.01554
jultemp	0.0017	1.76	0.00504	0.01176
janpcp	-0.0063	-3.16		
julpcp	-0.0194	-7.62		
			-0.00162	-0.00378

Saltwater Fishing Days

Negative Binomial Intensity Model				
Variable	Estimate	t-value	3F	7F
Intercept	2.4058	3.83		
income	0.0002	0.22		
white	-0.0609	-0.71		
male	0.24	3.93		
age	0.0031	1.35		
educ	-0.0686	-4.94		
hhnum	-0.068	-3.00		
under6	0.0419	0.83		
metro	0.0358	0.47		
jantemp	-0.0044	-1.22	-0.0132	-0.0308
jultemp	0.0128	1.47	0.0384	0.0896
janpcp	-0.0265	-1.46		
julpcp	0.117	5.74		
			0.0252	0.0588

A more structural damage function

- MRFSS data
  - temporal variation
  - Spatial variation
- Climate change would affect species composition and potential fishing days

Marine recreational fishing and climate change

- Household production model
  - HCKR = f(X; cs, ts)
  - Changes in season length
  - Changes in species composition
- Participation / Site selection model
  - Y = f(TC,HCKR; cs, ts)
- Estimate WTP with simulated changes of climate change

Conclusions

- No study to date explicitly addresses nonmarket valuation of climate change and marine resources
  - WTP review finds no mention of marine values
    - Is it insignificant or missing?
- Meta-analyses could be used in a benefit transfer study
  - Coral reef recreation values
  - Outdoor recreation values
  - Recreational catch values
- But, behavioral response to climate change is missing

Future Research

- All sorts of studies are needed: RP, SP; TEV, UV, NUV
- Most promising with existing RP data
  - Reduced form
  - More structural
- New studies
  - SP data
    - CVM – difficult to avoid double counting
    - CE – can differentiate between marine and other values
    - CB – behavioral response to climate change
  - RP-SP joint estimation
    - Can differentiate between UV and NUV

The impacts of climate change on terrestrial ecosystems

Karen Carney, Stratus Consulting Inc.

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analyses

Washington, DC

January 27-28, 2011

1. Background

Concerns over the impacts of rising global atmospheric greenhouse gas (GHG) concentrations are growing. Although human welfare and well-being will be directly affected by changes in climate, many important impacts to human welfare will occur indirectly due to climate-induced changes in ecosystems. Terrestrial ecosystems provide critical goods and services to humans. For example, they provide raw materials (e.g., food, water, and timber), regulate air quality, assimilate waste, and provide recreational opportunities. Terrestrial ecosystems are also valuable simply for existing; that is, society puts value on the existence of species and habitats and invests resources to protect them. To fully understand the benefits and costs of alternative climate policies, increases or declines in these critical services resulting from climate change must be evaluated.

It is well understood that climate is a key determinant of the structure and function of ecosystems. Climate affects which species are able to reside in a given location, how productive an ecosystem is, the rates of ecosystem processes (e.g., nitrification, methane production), and the nature, frequency, and intensity of natural disturbances (e.g., wildfires, pest outbreaks). Thus, as climate changes, it will fundamentally, and potentially dramatically, affect the location and character of ecosystems.

Which ecological impacts should be examined?

The Intergovernmental Climate Change reports, U.S. Climate Change Science Program synthesis reports, and a variety of other synthetic reports issued by states, governments, and NGOs provide a long list of potential impacts to terrestrial ecosystems. The impacts range across geographic scales (i.e., some are sub-national, country-specific, or global) and across different levels of biological organization (i.e., some address individual species, ecosystems, or global biodiversity). Which of these myriad of impacts should be addressed in integrated assessment models? I suggest that the focus be on impacts that are:

- Ecologically important – the impact is large and relatively widespread geographically

- Economically important – the impact will affect ecosystem services with high economic values

- Well understood – one needs to be able to project the magnitude of the impact in a scientifically robust manner.

2. Key terrestrial ecosystem impacts

Neither this abstract, nor the oral presentation that accompanied it, is intended to provide a comprehensive overview of terrestrial climate change impacts. Rather, I intend to highlight some of the key impacts and related tools that either have been or could be incorporated into integrated assessment models. Specifically, I discuss three large-scale terrestrial ecosystem impacts: (1) changes in vegetation distribution and dynamics, (2) changes in wildfire dynamics, and (3) potential increases in species extinction risks.

2.1 Changes in vegetation distribution and dynamics

Why climate change will affect vegetation dynamics. Climate is a fundamental driver of key ecological properties and processes. Temperature, precipitation, and relative humidity (and other climatic variables) affect where species can persist, ecosystem productivity, rates of ecosystem processes (e.g., organic matter decomposition), and frequency and intensity of disturbance events (e.g., wildfire, droughts, and pest outbreaks). Changing climate will thus fundamentally affect our environment, changing where grasslands and forests are located, the productivity of ecosystems, and kinds of disturbance regimes ecosystems experience.

Tools used to project changes in vegetation. Dynamic global vegetation models (DGVMs) are the most commonly used tool to project future changes in vegetation. Although many different models exist, typically all of them can address three specific issues: (1) how soil and climate affect the distribution of vegetation types, (2) how nutrients move within a given geographic area, and (3) wildfire dynamics. For a specific time period and climate change scenario, DGVMs can provide information about the potential distribution of vegetation types, the biomass of different types of vegetation (e.g., tree, shrub, grass), terrestrial carbon storage, and the frequency and extent of wildfires.

Examples of recent research. There has been a large volume of DGVM-related research over the past decade, and it is beyond the scope of this abstract to capture the history and evolution of that research. However, I will note that recent studies have used DGVMs to examine the impact of climate change on vegetation dynamics in specific countries, regions, and globally. For example, Lenihan et al. (2008) used the MC1 DGVM to demonstrate that there may be rather significant shifts in the distribution of vegetation in the United States by 2100 under climate change scenarios (based on the SRES A2 and B2 emissions scenarios). This study also showed that the extent of change in vegetation type and carbon storage is heavily influenced by fire suppression. Sitch et al. (2008) examined the potential impact of climate change on global vegetation and compared results across five DGVMs and four different SRES emissions scenarios. Their results showed substantial differences across models in vegetation responses to drought in the tropics and warming temperatures in boreal ecosystems. In this study, for all but the most extreme SRES scenarios (A1FI), the DGVMs suggested that the terrestrial biosphere would continue to be a sink throughout the 21st century. The stimulative effect of elevated CO_2 compensated for the direct suppressive effects of climate change on terrestrial carbon uptake. Galbraith et al. (2010) assessed the extent of projected Amazon forest die-back under future climate change using three DGVMs and the Hadley climate model (HadCM3). All DGVMs showed some degree of die-back, but the extent and intensity of the die-back varied significantly across DGVMs. Importantly, the models varied in their sensitivities to changes in rainfall and temperature; one model was equally sensitive to both changes in precipitation and temperature, but the other two were strongly affected by changes in temperature and insensitive to changes in precipitation.

<u>Key uncertainties and shortcomings in projections of vegetation change.</u> DGVMs can provide insights into the nature and magnitude of potential climate change impacts on terrestrial ecosystems, but there are important sources of uncertainty that should be kept in mind. First, these models provide information about "potential" vegetation only, ignoring the very real and critical impact that human intervention can have on the composition and productivity of vegetation. One can address fire suppression in DGVMs, and one can also screen out current and future urban and agricultural areas, but other effects (e.g., direct plantings, fertilization, invasive species) will be ignored. Second, many DGVMs assume there are no barriers to plant dispersal. This is clearly not the case, particularly in highly fragmented urban or agricultural landscapes. Third, the impacts of pests and pathogens are ignored, despite how critical these disturbance agents can be to shaping ecosystems. Finally, results across DGVMs can vary substantially for the same region and the same climate change scenario.

<u>Affected ecosystem services.</u> Changes in vegetation will affect a multitude of ecosystem services. Among the most important will be the provisioning of timber and non-timber forest products, grazing, and carbon storage and sequestration, which are critical to understanding potential terrestrial feedbacks to anthropogenic climate change.

2.2 Changes in wildfire frequency

<u>Why climate change will affect wildfire frequency.</u> Fires are likely to increase in many areas due to both the direct and indirect effects of climate change. Higher temperatures will directly increase the likelihood of fires – a spark is more likely to turn into a fire when temperatures are hotter. Higher temperatures also desiccate vegetation and forest floor, which provide the fuel for fires. Indirect effects on fire can be brought about via changes in vegetation. For example, grasslands burn more readily than forests. And changes in productivity affect fuel load.

<u>Tools used to project changes in wildfire.</u> In my review of the literature, I identified two main approaches to projecting wildfire under climate change. The first is to use statistical modeling. This involves examining past fire behavior and identifying the factors that best predict historical fire outbreaks (e.g., via step-wise linear regression). Changes in these factors are then used to

predict fire behavior in the future. The second approach involves utilizing the relatively simplistic fire models embedded in DGVMs to project future fire dynamics.

Examples of recent research. As with the review of dynamic global vegetation modeling, this section is not at all meant to be comprehensive, but rather to highlight studies that demonstrate the kinds of analysis that can be (and have been) done in this field recently. Many studies have been done at relatively small scales or at the country level, but here I'll mention two global studies, as that is the scale most relevant for integrated assessment models. Gonzales et al. (2010) used output from the fire model of MC1 to develop estimates of changes in fire frequency between 2000 and 2100 under SRES scenario A1B. They found the fire frequency decreased on two-fifths of global land, just slightly more than the area experiencing increases. Areas with potentially lower fire frequencies included the coterminous United States. and northern Eurasia; higher fire was projected for sub-Saharan Africa and northern South America. Krawchuk et al. (2009) used statistical modeling to estimate changes in fire probability under SRES scenarios A2 and B2. Some of their results agree with Gonzales et al. (2010) – decreases in fire probabilities are projected in northern Eurasia and higher fire probabilities are projected for South America. However, Krawchuck et al. (2009) found that fire probabilities would be higher in the United States and Europe and lower probabilities are estimated in sub-Saharan Africa.

Key uncertainties and shortcomings in projections of wildfire. For both statistical modeling and DGVM approaches to projecting future fire, the models only roughly approximate historical patterns of fire. They thus can only be expected to provide relatively rough indices of what might happen with fire in the future. Like DGVM studies, the results of fire modeling studies can vary significantly for the same region, and it is difficult for non-experts to assess which results are more accurate. Finally, the timing and location of specific fires cannot be projected – only rough approximations in overall changes in fire frequency and intensity for a given location can be provided.

Affected ecosystem services. Like changes in vegetation, fire will affect the provisioning of timber and non-timber forest products. Fire will also affect recreation, as people tend to stay away for a period of time from areas that have recently burned before they return to hike, fish, or camp. Although not an ecosystem service, changes in fire dynamics could also affect the amount of money that is spent on fire suppression, an effect not likely addressed by other sectoral analyses addressed in integrated assessment models. Finally, wildfire could have important effects on air quality via the release of aerosols, which would have important health and visibility implications.

2.3 Potential increases in species extinction risks

Why climate change will affect species extinctions. As noted earlier, climate is a critical driver of where different species and ecosystems are found. As climate shifts, the areas providing the climatic conditions that a species requires may move, sometimes into areas that don't have any habitat that could support that species (e.g., into agricultural or urban areas). It is also possible that the climatic conditions a species requires may disappear altogether. This is more likely to occur with species that live at high altitudes or latitudes.

Tools used to project changes in species extinction risks. There are a variety of approaches that can be used to estimate the risk of future species extinctions. However, the most commonly used approach involves the application of climate envelope models. These models use information about the current distributions of species and the associated range of climate conditions to construct their climate requirements. Under future climate scenarios, one estimates where that species could live and how much area is available to it. Some studies then use species-area relationships (species diversity is known to increase with size of geographic area) to determine how many species can be supported in a future climate. Climate envelope models can be used alone or in conjunction with expert opinion to estimate species extinction risks. Another, less commonly used approach for examining future extinction risks involves utilizing vegetation models to estimate habitat loss within a specific geographic area under different climate change scenarios; such analyses often make the simplifying assumption that species ranges cannot shift to accommodate changes in habitat (Pereira et al., 2010).

Examples of recent research. Estimates of species extinctions vary widely. For example, Thomas et al. (2004) estimate that between 9 and 52% of species would be committed to extinction by 2050, depending on the assumptions made about dispersal ability and the specific climate change scenario. The IPCC (2007a) estimated, using a combination of expert judgment and information from climate envelop studies, that 20 to 30% of plant and animal species would be at risk of extinction with an increase of 2 to 3ºC in global temperature. A range of studies, using quite different methodologies and examining different taxa, found that from 0 to 60% of species may be at risk of extinction under future climate change (Pereira et al., 2010). Interestingly, Beale et al. (2008) found that climate envelop models did no better than chance in explaining why species reside where they do for approximately two-thirds of European bird species.

Key uncertainties and shortcomings in estimates of future extinction risks. Although climate change poses a real, critical threat to species across the globe, there is a great deal of uncertainty both within and among modeling studies about the magnitude of climate change impact on species extinctions. Climate envelope models are known to have some specific technical issues; these issues need to be specifically addressed because these types of models are used so often. First, they may overestimate extinctions because species may be more flexible climatically than their current distribution suggests. Envelope models may also underestimate extinctions because climate change may interact with other factors, making things worse than predicted. For example, some species may not be able to persist near human settlements even if the climate is suitable.

Affected ecosystem services. Understanding the economic impact of global-level species extinctions is another challenge. Economic studies have been done to estimate the existence values of species, but these studies can be highly controversial. The impacts of extinctions on other services could be explored, given the services that specific species or suites of species can provide. For example, a tree species may provide valuable wood, and bird and wildlife viewing provide another type of value. However, such values are typically tied to species or geographic locations rather than global extinctions, making this approach impractical.

3. Future research needs

3.1 Integrating across studies

Across all ecosystem impacts, there are a variety of methods available to project future dynamics, and the methods typically give different answers regarding the magnitude of the impact in question. The question is – how should all the different tools and studies be integrated? Some ideas include:

- Conducting meta analyses, which involves pooling data across many studies to detect general patterns.

- Developing ensemble means, as is done for climate models, across different impact models. This approach would likely require ensembles to be developed across different climate change scenarios and GCMs, making its feasibility questionable.

- Soliciting expert opinions. Although imperfect and subjective, this is a cost-efficient method for providing rough estimates of the potential direction and rough magnitude of specific impacts.

3.2 Key knowledge gaps

There are also some critical knowledge gaps that need to be addressed when considering the kinds of impacts that would appropriately be addressed in integrated assessment models. Three key gaps include:

- <u>Pest outbreaks.</u> There is a dire need for models that project the impact of climate change on pest outbreaks. We know that pests are critical drivers of the productivity and structure of ecosystems and that they will have significant impacts on the provisioning of ecosystem services.

- <u>Freshwater wetlands.</u> Large-scale, interior, freshwater wetlands provide critical ecosystem services, and it is clear they will be affected by changes in precipitation and temperature. Although some models have been developed to conduct sensitivity analyses related to wetland impacts, projections of impacts for specific regions (e.g., the Prairie Pothole region) are needed.

- <u>Snow pack dynamics.</u> A lot of research has examined the impact of climate change on snow pack dynamics, but this research has typically focused on water resource implications. Changes in snow pack volume and the timing of snow pack melt can affect freshwater and marine ecosystems as well as snow-related recreation.

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The Impact of Climate Change on Terrestrial Ecosystems

Climate Damages Workshop

Karen Carney, PhD
Stratus Consulting
Washington, DC
January 28, 2011

Outline

- Background
- Descriptions of key ecosystem impacts
  – Vegetation distribution and dynamics
  – Wildfire dynamics
  – Species extinction risks
- Future research needs

Background

- Why do ecosystems matter when assessing economic impacts of climate change?
- Provide critical services to people
  - Provisioning (e.g., food, water, raw materials)
  - Regulating (e.g., air quality, storm protection, waste assimilation)
  - Cultural (e.g., recreation, passive use)
- These services have substantial economic value

Background (cont.)

- Climate change affects:
  - What species are where
  - How productive an ecosystem is
  - Rates of ecosystem processes (e.g., decomposition, denitrification)
  - The disturbance regimes it experiences
    - Drought
    - Fire
    - Pest outbreaks

Photo credits: USFWS

Background (cont.)

- Which ecological impacts?
- Given focus on use in integrated assessment models, focus on impacts:
  - Ecologically important
    - Impact is large and relatively widespread
  - Economically important
    - Impact will affect ecosystem services with high values
  - Well understood
    - Need to quantify projected impacts in scientifically robust way

Outline

- Background
- Descriptions of key ecosystem impacts
  - Vegetation distribution and dynamics
  - Wildfire dynamics
  - Species extinction risks
- Future research needs

Key Ecosystem Impacts

- For each impact, will discuss:
  - Why the impact is likely to occur
  - The tools available to estimate the impact
  - What research has shown
  - Key uncertainties or other shortcomings with projecting future impacts
  - What key services are likely to be affected

Outline

- Background
- Descriptions of key ecosystem impacts
  - Vegetation distribution and dynamics
  - Wildfire dynamics
  - Species extinction risks
- Future research needs

Changes in Vegetation

- How will climate affect vegetation?
  - Changes in temperature, precipitation, relative humidity affect:
    - What species can live where
    - Ecosystem productivity
    - Wildfire frequency and intensity, a key disturbance agent
  - Will fundamentally alter our environment – where grasslands and forests are, and what kinds of animals we see in different areas (not static)

Changes in Vegetation (cont.)

- Projecting future vegetation dynamics
  - Dynamic global vegetation models (DGVMs)
    - Large scale patterns of vegetation change
    - Typically have interacting modules:
      - Biogeography model – potential vegetation given climate and soil parameters
      - Biogeochemistry model, which simulates the movement of nutrients
      - Fire model – disturbance by wildfire

Changes in Vegetation (cont.)

- Projecting future vegetation dynamics (cont.)
  - For specified time period and climate scenario, DGVMs can tell you:
    - Potential vegetation type (e.g., temperate deciduous forest, temperate mixed forest)
    - Plant biomass (by life form – trees, shrubs, grasses)
    - Carbon storage (above and below-ground)
    - Burned area/wildfire frequency

Changes in Vegetation (cont.)

- Projecting future vegetation dynamics (cont.)
  - Many DGVMs are available; commonly used:
    - MC1 – United States
    - Lund-Potsdam-Jena (LPJ) – Germany/Sweden
    - SDGVM – United Kingdom
    - Integrated Biosphere Simulator (IBIS) – United States

Changes in Vegetation (cont.)

- What research has shown

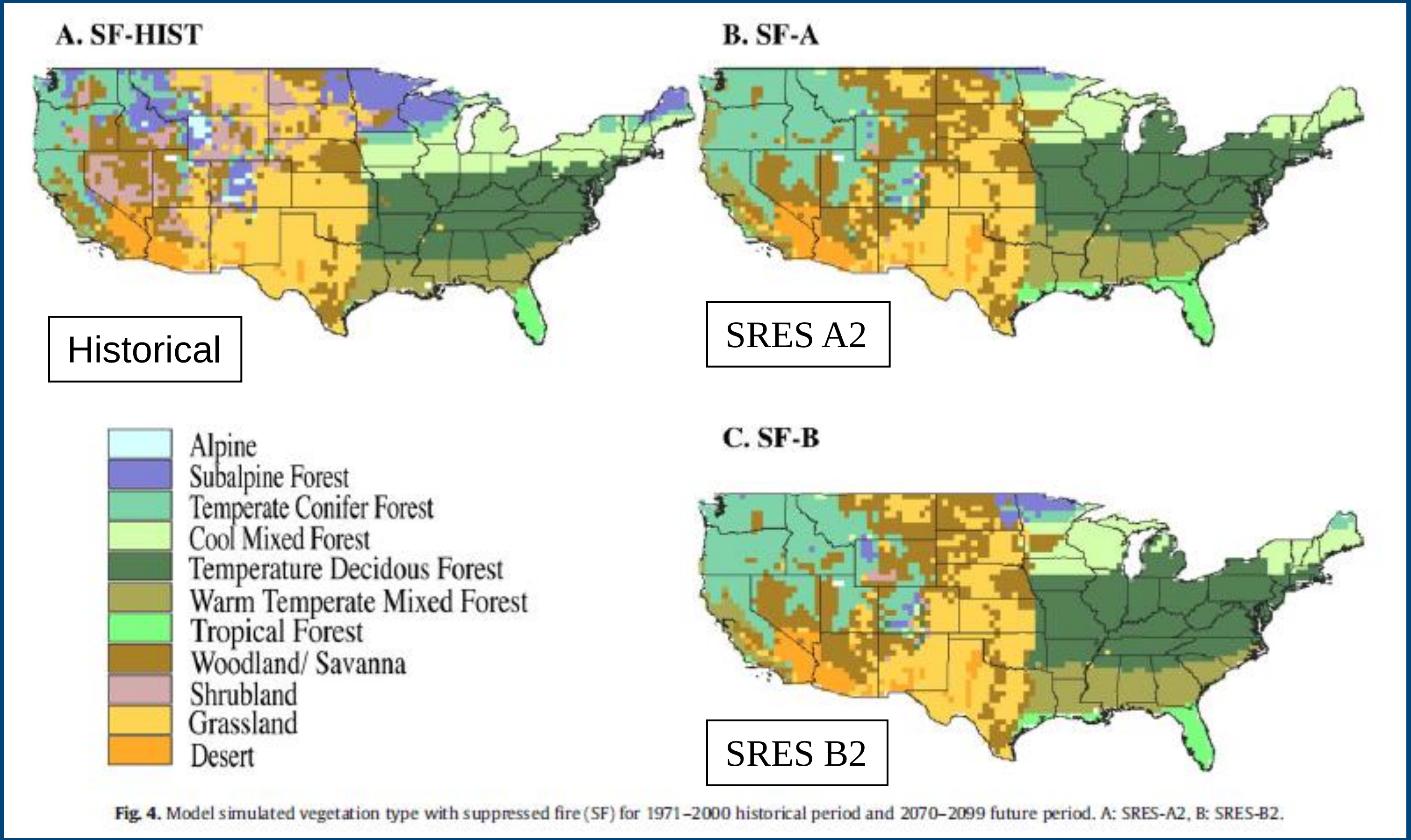
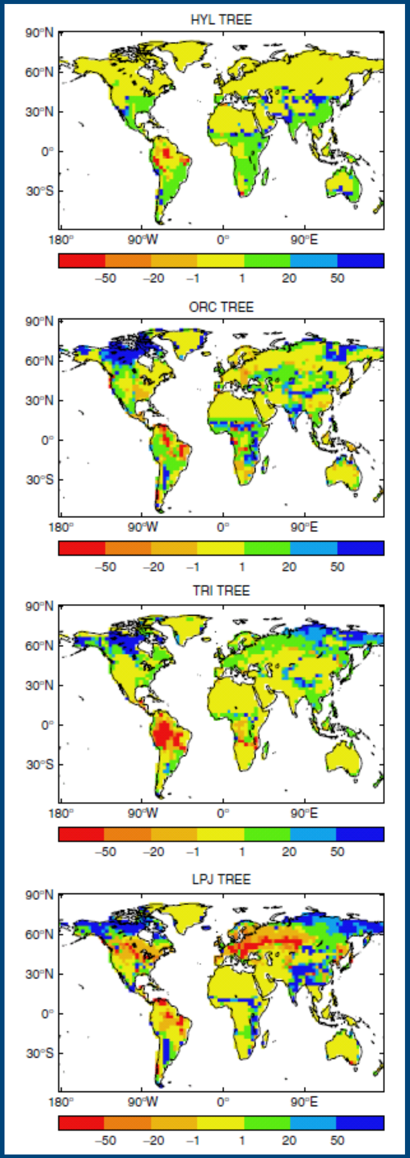


Fig. 4. Model simulated vegetation type with suppressed fire (SF) for 1971–2000 historical period and 2070–2099 future period. A: SRES-A2, B: SRES-B2.

From: Lenihan et al., 2008. *Global and Planetary Change* 64:16–25.

Changes in Vegetation (cont.)

- <u>What research has shown (cont.)</u>
  - % change in tree coverage, SRES A1FI, 4 DGVMs, Hadley GCM
  - Significant variability across models
  - Some areas of general agreement
    - Varying degrees of Amazon forest dieback
    - Boreal forest expansion



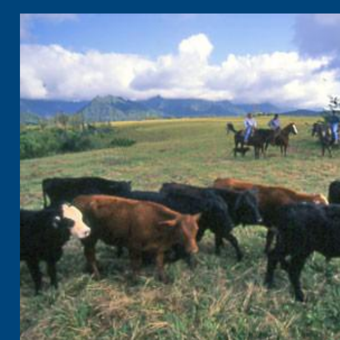
From: Sitch et al., 2008. *Global Change Biology* 14:2015–2039.

Changes in Vegetation (cont.)

- Key uncertainties
  - *Potential* vegetation only – most anthropogenic factors ignored; some can be addressed
    - Fires suppression can be accounted for
    - Can screen out urban/agricultural lands
  - Assume no barriers to plant dispersal
  - Pests and pathogens are ignored
  - Significant differences across DGVMs for the same region and climate scenario

Changes in Vegetation (cont.)

- Affected ecosystem services
  - – Forestry
    - Timber
    - Non-timber forest products
  - – Grazing
    - Forage productivity in grasslands, shrublands, savannas, and forests
  - – Carbon sequestration and storage



Changes in Vegetation (cont.)

- <u>Take home</u>
  - – Ecosystems across the globe will be affected, so this is a key impact to consider
  - – Can examine multiple scales – countries, regions, the globe
  - – Linked to critical ecosystem services
  - – Good models, but difficult to know which ones are most reliable
  - – Highly dependent on the GCM used
  - – Look for areas of agreement, perhaps average DGVM results when possible

Outline

- Background
- Descriptions of key ecosystem impacts
  - Vegetation distribution and dynamics
  - Wildfire dynamics
  - Species extinction risks
- Future research needs

Wildfire Dynamics

Photo credit: USFWS

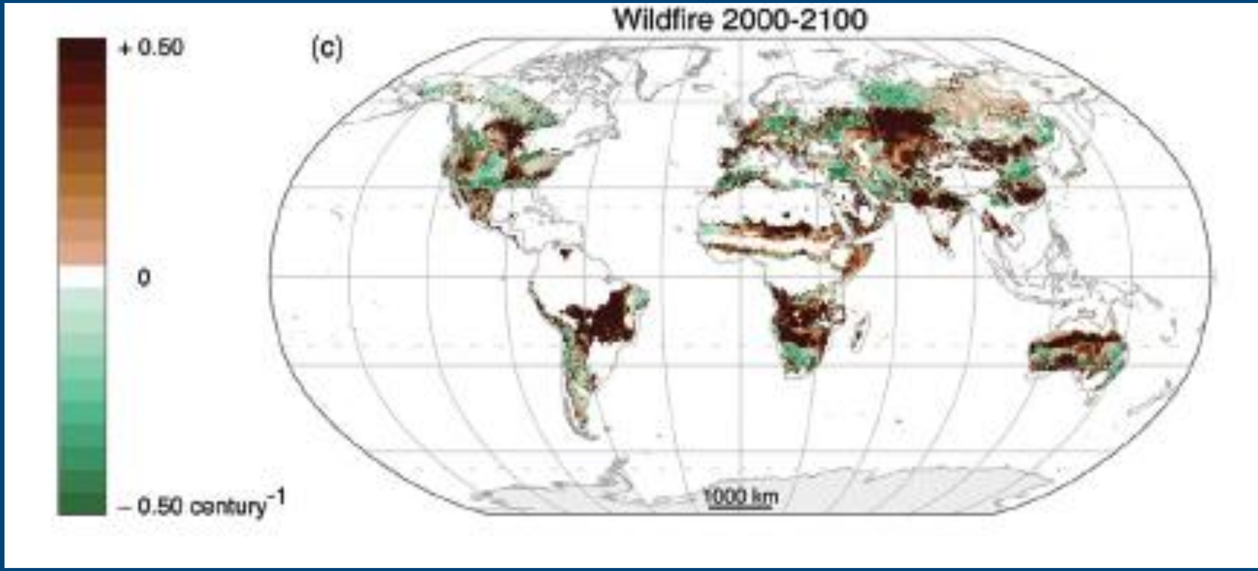
- <u>How will climate affect wildfire?</u>
  - Fires will likely increase in many areas via various mechanisms
    - Direct
      - Higher temperatures = more fires
      - Higher temperatures (and decreased precipitation) = desiccation of vegetation and forest floor (fuel)
    - Indirect
      - Changes in vegetation type (grassland/forest)
      - Changes in productivity (fuel load)

Wildfire Dynamics (cont.)

- Projecting future wildfire dynamics
  - Statistical models
    - Examine past fire behavior
    - Identify factors (e.g., via stepwise linear regression) that are key to predicting fire
    - Use equation to predict fires in future (based on key variables)
  - DGVMs

Wildfire dynamics (cont.)

- <u>What research has shown</u>
  - Change wildfire freq. from 2000-2100, A1B
  - More fire: U.S., central South America, southern Africa, western China, Australia
  - Less fire: northern Canada, northern Russia



From: Gonzales et al. 2010. *Global Ecol. Biogeogr.* 19: 755-768

Wildfire Dynamics (cont.)

- Key uncertainties
  - For both statistical model and DGVM approaches
    - Methods only roughly approximate historical fires
    - Thus, provide similarly rough estimates of future wildfire dynamics
    - Timing/locations of specific fires cannot be predicted

Wildfire Dynamics (cont.)

Photo credit: USFWS

- <u>Affected ecosystem services</u>
  - Timber/non-timber forest product provisioning
  - Recreation
  - Fire suppression (not an ecosystem service but a real cost)
  - Regulation of air quality – aerosols (see Spracklen et al., 2009, *Journal of Geophysical Research*)

Photo credit: USFWS

Outline

- Background
- Descriptions of key ecosystem impacts
  - Vegetation distribution and dynamics
  - Wildfire frequency/intensity
  - Species extinction risks
- Future research needs

Species Extinctions

- <u>How will climate affect it?</u>
  - Climate (temperature/precipitation) is a key driver of species and ecosystem distributions
  - As climate shifts, areas that support specific species may move (sometimes into areas inhabited by humans)
  - Habitat may disappear (e.g., alpine, cloud-forest dependent species)
  - These dynamics will likely increase the risk of species extinctions

Photo credits: USFWS

Species Extinctions (cont.)

- Projecting future species extinctions
  - Most commonly involves application of "climate envelope" models
    - Use current distributions of a species to construct its climatic requirements
    - Under future climate change, then determine where species could live
    - Use species-area relationships to project extinctions

Species Extinctions (cont.)

- <u>What research has shown</u>
  - – Results vary
    - 9–52% of species will be “committed” to extinction by 2050 (Thomas et al., 2004)
    - 20–30% of plant and animal species at risk of extinction with increase of 2–3 C (IPCC, 2007)
    - 0–60% extinctions for different taxa/methodologies (Pereira et al., 2010)
  - – Envelope model did no better than “null” models in predicting species occurrence (null = species ranges are randomly placed in region; Beal et al., 2010)

Species Extinctions (cont.)

- <u>Key uncertainties</u>
  - Great deal of uncertainty within and across studies and modeling methods
  - Climate envelope models
    - May overestimate extinctions
      - Species may be flexible climatically
      - Biotic interactions may be more important than climate
    - May underestimate extinctions
      - Dispersal may be limited by habitat fragmentation
      - Impacts of climate change may be amplified by land use change

Species Extinctions (cont.)

- Affected ecosystem services
  - – Another key issue…
  - – How do you value global biodiversity?
    - Could query public
      - – Some species may matter more to the public, and ecologically, than others

Species Extinctions (cont.)

- Affected ecosystem services (cont.)
  - Values could be tied to specific species, or suites of species
    - A given tree may provide highly valued wood
    - Bird watching/wildlife viewing is valuable
  - But values not tied to global extinction risk – linked to species, suites of species, and/or specific locations

Species Extinctions (cont.)

- Take home
  - Climate change is a threat to species, and more extinctions are likely to occur
  - Range of estimates available for species extinction risk
  - Robustness of estimates highly contested
  - Link to ecosystem services and values difficult
  - Proceed with caution

Outline

- Background
- Descriptions of key ecosystem impacts
  - Vegetation distribution and dynamics
  - Wildfire frequency/intensity
  - Species extinction risks
- Future research needs

Photo credit: USFWS

Future research

- <u>Integrating across approaches</u>
  - Across all impacts, variety of methods available that provide different estimates of impact
  - Need to think carefully about how to integrate across studies/tools
    - Meta-analyses?
    - ‘Ensemble means’ of ecosystem impacts with different models?
    - Need to be done with different climate scenarios/GCMs
    - How can this be done practically?

Future research (cont.)

Photo credit: USFWS

- Major Gaps
  - Need to develop large-scale, long term projections for changes in
    - Pest outbreaks
    - Interior wetland change/loss
  - Changes in snow pack dynamics
    - Large-scale impacts on freshwater/marine ecosystems
    - Implications for recreational values

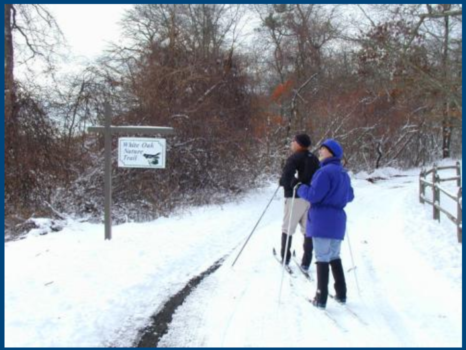
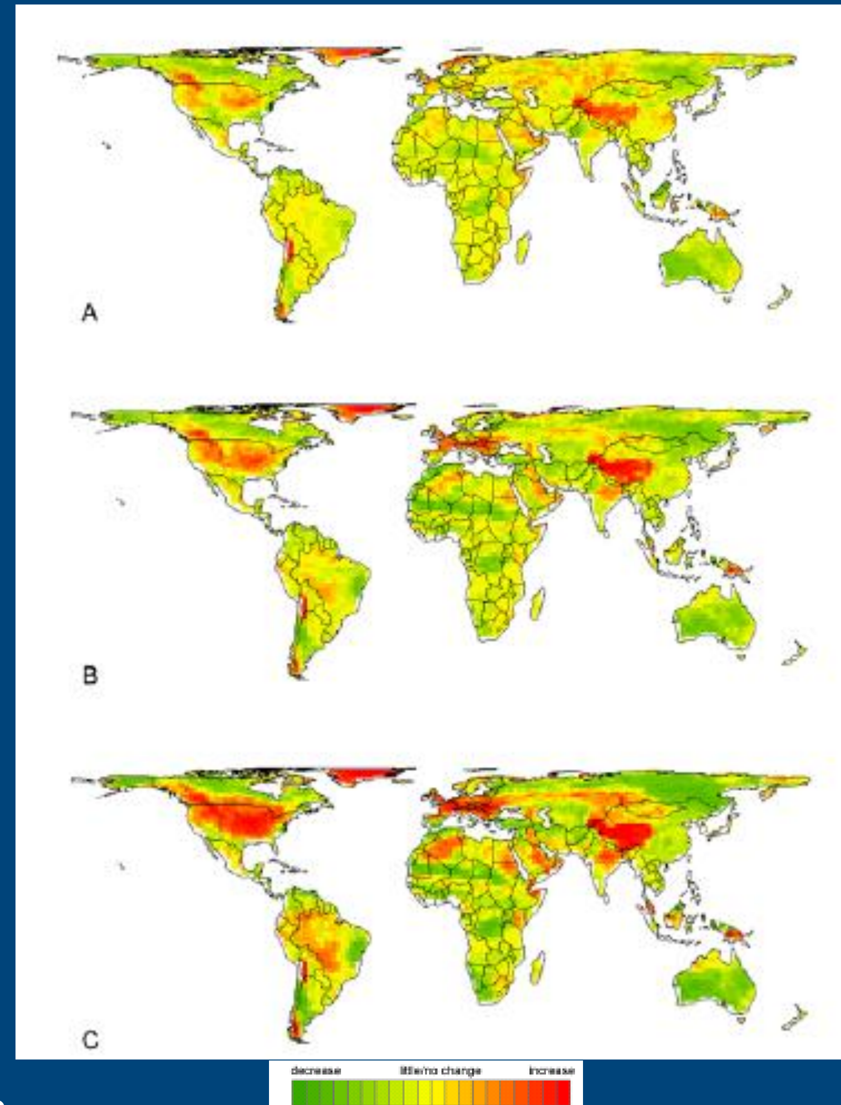


Photo credit: USFWS

Photo credit: USFWS

Wildfire Dynamics (cont.)

- What research has shown
  - Fire risk for three different time periods over 21st century
  - Higher fire risk:
    - U.S.
    - Amazon
    - Western China
  - Lower fire risk:
    - Northern Canada
    - Russia
    - Australia (?)



From: Krawchuck et al., 2009. *Plos One* 4: e5102.

Valuing the impacts of climate change on forestry

Brent Sohngen (Ohio State University)

1. Briefly review the existing estimates of the value of climate change impacts on forestry. In addition to the best central estimates, also describe the wider range of possible outcomes—including those that may arise from potential economic catastrophes—and the relative likelihoods of these outcomes.

Current estimates suggest that forestry outputs are likely to increase globally over the century (see Table 1). As a result, consumers will gain from increased timber output and lower timber prices. Producers could gain if timber production increases due to climate change, although lower prices could have negative impacts in some regions (for discussion of overall welfare impacts, see Sohngen et al., 2001). The strongest gains are projected for subtropical regions where producers are able to adapt more quickly with faster growing timber types.

Table 1: Estimates of impacts of climate change on timber outputs by region (reproduced from Table 4.2 in Seppala et al., 2004).

Region	**Output**		**Producer Returns**
	2000–2050	2050–2100	
North America[1]	-4% to +10%	+12 to +16%	Decreases
Europe[2]	-4% to +5%	+2 to +13%	Decreases
Russia[3]	+2 to +6%	+7 to +18%	Decreases
South America[4]	+10 to +20%	+20 to +50%	Increases
Australia/New Zealand[4]	-3 to +12%	-10 to +30%	Decreases& Increases
Africa[5]	+5 to +14%	+17 to +31%	Increases
China[5]	+10 to +11%	+26 to +29%	Increases
South-east Asia[5]	+4 to +10%	+14 to +30%	Increases

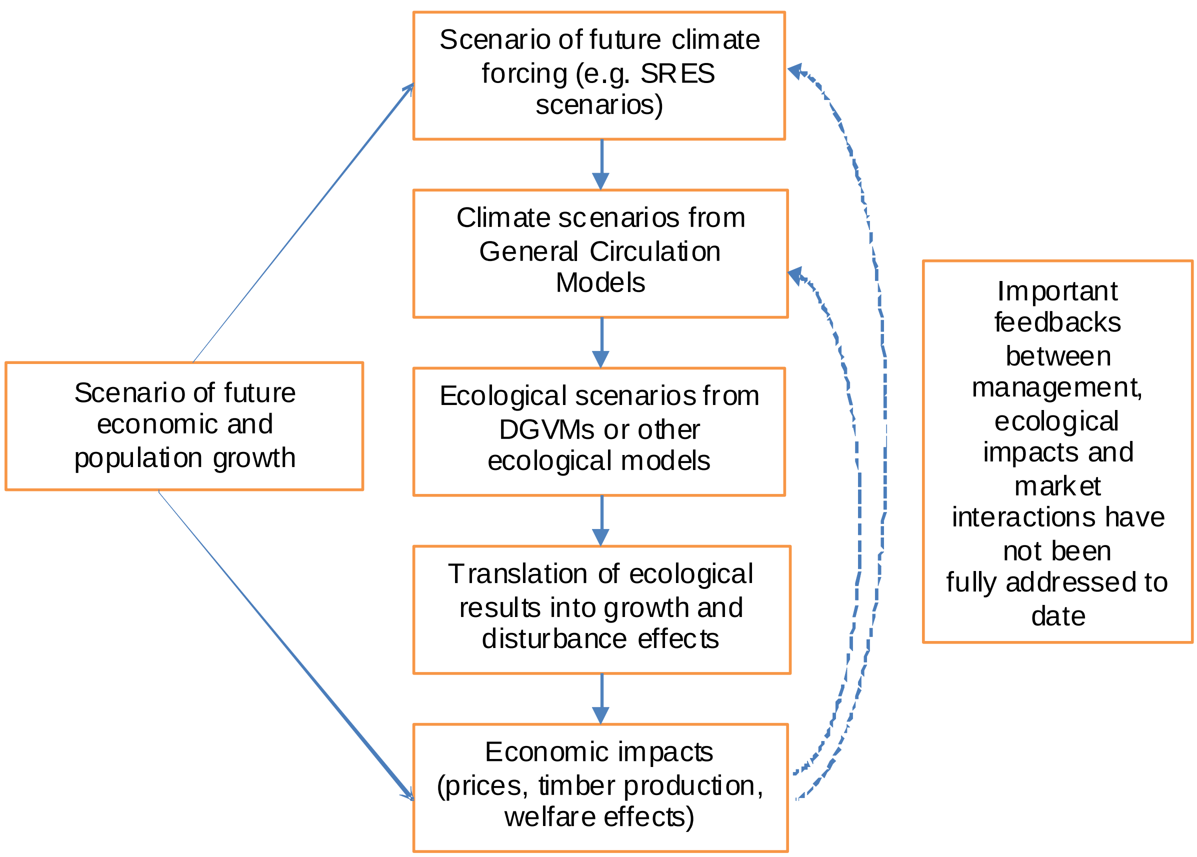
[1] Alig et al. (2002), Irland et al. (2001), Joyce et al. (1995, 2001), Perez-Garcia et al. (1997, 2002), Sohngen et al. (2001), Sohngen and Mendelsohn (1998, 1999), Sohngen and Sedjo (2005)
[2] Karjalainen et al. (2003), Nabuurs et al. (2002), Perez-Garcia et al. (2002), Sohngen et al. (2001)
[3] Lelyakin et al. (1997), Sohngen et al. (2001)
[3] Lelyakin et al. (1997), Sohngen et al. (2001)
[4] Perez Garcia et al. (1997, 2002), Sohngen et al. (2001)
[5] Sohngen et al. (2001)

Although the general results suggest higher output in forestry, there is large uncertainty about these results. The ranges shown in Table 1 are not uncertainty bounds, but they are instead ranges based on different studies in the literature. These do not reflect the full set of uncertainty that would be expected to affect estimates of economic impacts, but they are illustrative of the current state of knowledge.

One of the difficulties of measuring uncertainty in economic outcomes relates to method used to conduct integrated assessment modeling of forestry impacts. Figure 1, for example, represents the typical modeling steps that are undertaken to calculate the impacts of climate change on forestry. Modelers start with the climate models, which are linked to ecosystem models, which are in turn linked to economic models. All of the models have their own uncertainties, and researchers will handle these uncertainties in different ways, depending on the resources they have to conduct a study.

For example, uncertainty in climate outcomes from the climate models can be incorporated, at least tentatively, by utilizing several different models. There are a large number of climate models, and if researchers have access to many of them, they can choose them in order to represent the range of potential outcomes from the models. The ecosystem models, nowadays the Dynamic Global Vegetation Models (DGVMs), also contain uncertainty. There are fewer ecosystem models than climate models, but in the past, research teams have collaborated to prepare results across different ecosystem models based on common climate inputs (e.g., VEMAP Members, 1995). In these cases, the research teams have represented at least some of the uncertainty in ecosystem outcomes by using results from several models.

Figure 1: Flow of forestry integrated assessment models of climate change impacts (from Seppala et al., 2009)



2. How do these estimates vary across regions? Characterize the uncertainty / robustness / level of confidence in these estimates, on average globally and by region.

The results in table 1 suggest potential negative effects in the shorter-term in temperate regions like the United States, Canada, Europe, Russia, etc. There are several reasons for this. The ecological models utilized in the studies in Table 1 suggested that climate change could cause relatively large disturbances in forests over the next several decades, and these disturbances could negatively influence outputs. While the impacts are mitigated to some extent by adaptation through salvage harvesting, the changes in disturbance patterns modeled by the ecological models were large enough to have important impacts.

In contrast, most subtropical and tropical regions are projected to potentially benefit from climate change according to the results in Table 1. These trends are anticipated to continue. Over the past half century, there has been a continued increase in the area of fast-growing timber plantations in subtropical regions world-wide. Current estimates suggest that there are 90-100 million hectares of fast-growing timber plantations globally with20-40 million of these hectares located in subtropical regions (ABARE-Jaako-Poyry, 1999; Sohngen, 2010). They are estimated to provide 15-25% of global timber supplies currently (Daigneault et al., 2008; Sohngen, 2010), and are expected to provide much of the growth in output in the coming decades. The fast-growing plantations have timber species that can be harvested in 10-25 year rotations and produce 10-20 m^3 per hectare per year in wood (Cubbage et al., 2010).

Economic studies suggest that managers are able to adapt to climate change relatively rapidly with these fast-growing plantation species. As supplies in temperate zones are affected by disturbances, supply of timber from plantations expands to limit any shortfalls globally. In fact, managers of plantation forests appear to be able to take advantage of some of the impacts of climate change in forests that have longer rotations. Furthermore, ecosystem models used in the earlier economic studies did not suggest as large of disturbance patterns in subtropical regions as in temperate regions, so plantations were exposed to less risk than their counterparts further north.

As noted above, it is difficult to quantify the uncertainty in economic outcomes. Most of the studies conducted so far are greater than 5 years old, and thus are reliant on climate and ecosystem modeling that occurred in the early to mid-1990s. This constitutes an important limitation to the robustness of the result described above. Utilizing more recent climate and ecological modeling may lead to very different estimates of economic impacts.

3. Briefly review the models and data used to estimate the value of climate change impacts on forestry.
    a. What types of natural science models and data are used to inform these estimates, and what categories of values have been included?

A number of different ecosystem models have been used to date by economic modelers. For example, the models in the study by VEMAP Members (1996) have been used by a number of different modelers to examine economic effects of climate change. These earlier models have been supplanted by more recent Dynamic Global Vegetation Models (e.g., Fischlin et al., 2007;

Bachelet et al., 2003, Bachelet et al., 2004). These models project changes in ecosystem type, changes forest productivity (net primary productivity, net ecosystem productivity, and net biological productivity), and in some cases changes in carbon content due to fire or other disturbances. The models can be implemented at a range of scales depending on the inputs. Often, for example, they are implemented globally at the 0.5 degree grid cell basis; however, they can be implemented at a finer scale for more specific regional analysis. For climate analysis, however these models all rely on climate model inputs, which are often provided at a much more aggregate level.

b. What physical and economic factors make some regions more or less vulnerable to the impacts of climate change on forestry than others?

The most vulnerable regions to climate change in forestry appear to be regions that currently produced the greatest share of output. For instance, in the United States, the Southern US produces the greatest share of output nationally and is also projected to be the most vulnerable in analyses to date (e.g., Sohngen and Mendelsohn, 1998, 1999; Sohngen et al, 2001; Bachelet et al., 2003; Bachelet et al., 2004). In a global context, the study by Sohngen et al. (2001) suggests that North America, Europe, and Russia are more vulnerable to climate change than other regions due to ecological and economic factors. Note that these regions currently constitute over 65% of industrial timber outputs. Ecologically, the models suggested that these regions would experience greater disturbance with climate change. Economically, these temperate regions could adapt, but because other regions were able to adapt more rapidly, prices fell, and the lower prices reduced welfare for landowners in temperate regions.

The physical factors that make a region more or less vulnerable relate mainly to the growth rate of the timber stocks and the area of fast-growing plantations. Regions with faster growing species appear to be more able to adapt to climate change, whereas regions with slower growing species appear to be more susceptible to damages from forest fires and other impacts.

c. How are the values of forestry impacts projected into the future, accounting for changes in other economic and environmental conditions?

For the most part, process based economic models are utilized. These models used either dynamic optimization approaches, or other static simulation approaches to projection timber harvests. Most studies have made timber price endogenous so they are able to account for other factors that influence timber demand, such as changes in population and income.

4. What are the most important gaps or uncertainties in our knowledge regarding the value of forestry impacts? What additional research in this area would be most useful?

There are a number of important gaps. Three potential gaps and additional research topics are listed below:

- The pace of change in ecosystem and climate models appears to be much more rapid than the pace of change in economic modeling. For example, new scenarios of climate models and new scenarios of ecosystem models seem to appear about every 5 years, while new economic analysis emerges much more slowly.

There may be a number of reasons for this. One possible explanation is that the effect of humans on forested ecosystems is changing dramatically. The economic studies reviewed above focus on timber demand as the driving human influence; however, timber demand may not be the most important demand of forest resources in the future. For example, future demand for natural ecosystems may be driven by non market vaues or recreational values, or it may be driven more importantly by land-use change (e.g., conversion of productive timberland to private recreational land). Alternatively demand may be driven by agricultural uses in some regions of the world (e.g., tropical regions where agricultural land is expanding). Thus, more complex models that account for different kinds of demands for land may be necessary to fully assess the implications of climate change on forestry.

- The economic models have not fully reflected the uncertainty. The ecosystem models suggest that disturbance patterns could change dramatically over time, but there has been little use of this information by economic modelers to date. There are a number of stochastic models of forest management under uncertain disturbance regimes (e.g., Daigneault et al., 2010), but few of these are linked to climate models .

- Ecosystem models are calibrated without reference to models of human behavior. This likely causes them to over-estimate the potential effects of climate change on ecosystems. In many ecosystems, for instance, one would expect humans to adapt to damages, and this adaptation is missing from the ecosystem models. There is substantial room for modelers to conduct integrated economic and ecological analysis that would capture these effects.

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Estimating the Economic Impact of Climate Change on Forestry

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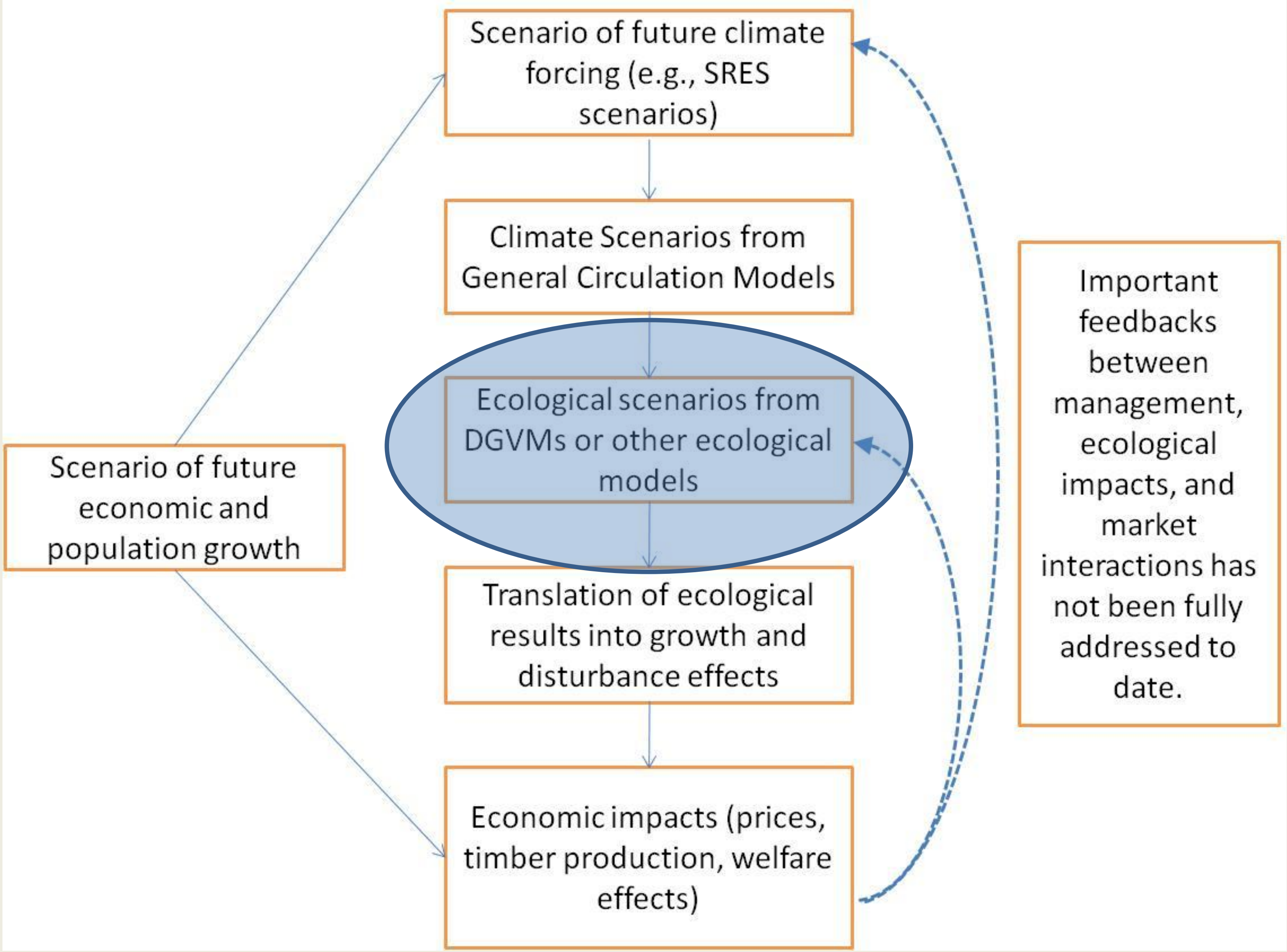
Outline of Presentation

- Methods for assessment
- Ecosystem impacts important for economic analysis
- Some results from a recent assessment.

How are impacts measured?



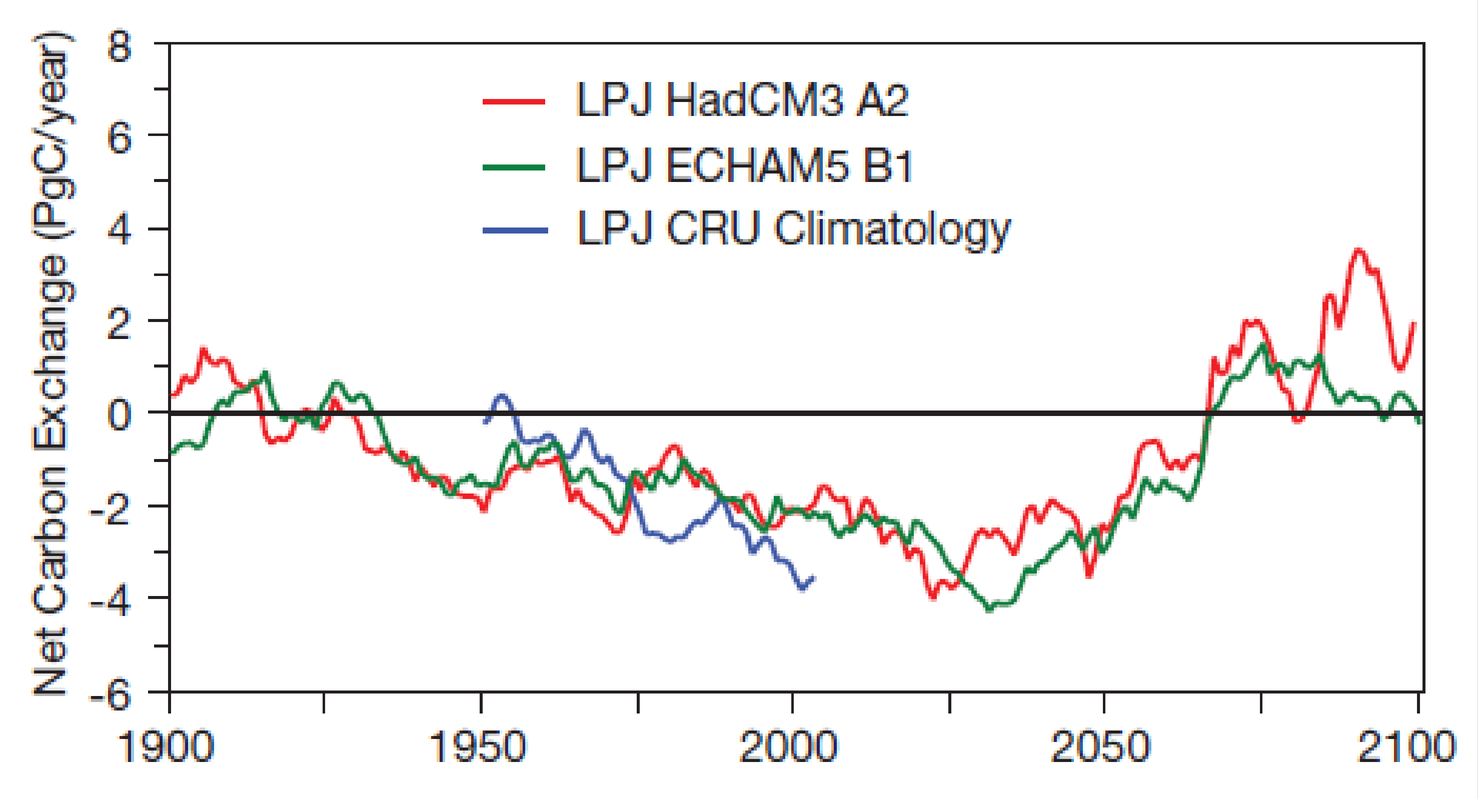
Adaptation of Forests and People to Climate Change. 2009. Alexander Buck, Pia Katila and Risto Seppälä. (eds.). IUFRO World Series Volume 22. Helsinki. 224 p.

Ecosystem Impacts

- Productivity changes (IPCC, 2007)
  - CO_2 fertilization (e.g., Norby et al., 2006).
  - Warming in colder climates.
  - Precipitation gains where water is limited.
- Some current evidence that historical climate change and CO2 change have increased productivity to date (e.g., Myneni et al., 1997; Boisvenue and Running, 2006; McMahon et al., 2010).
- Potential limits to productivity gains: Net impacts
  - Species composition, age structure, seasonal and daily precipitation and temperature patterns, etc.
  - Drying and forest fire effects

Global Ecosystem Impacts

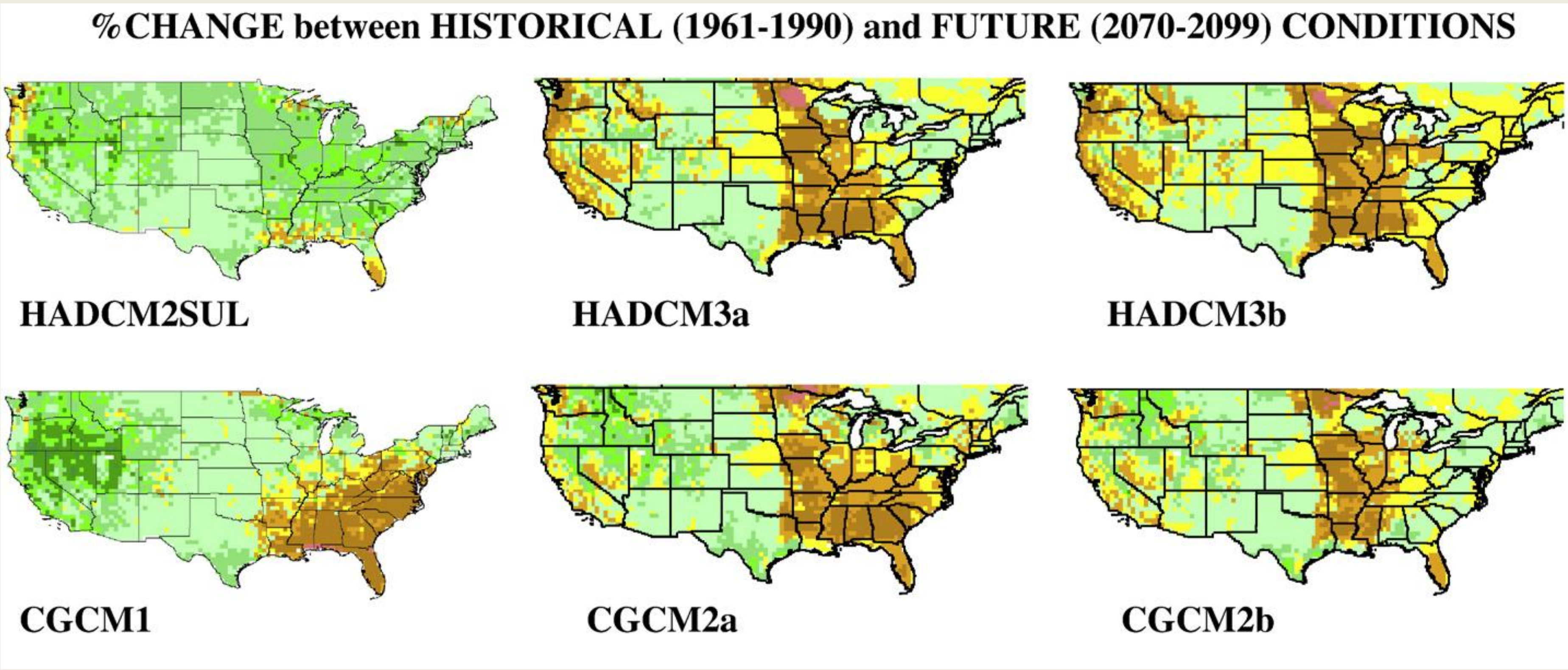
- *Losses ultimately weigh down gains:* Ecosystems turn from carbon sink to source within the next several decades, due to fire and other disturbance



IPCC (2007) WG 2, Chapter 4, Figure 4.2

US Ecosystem Impacts

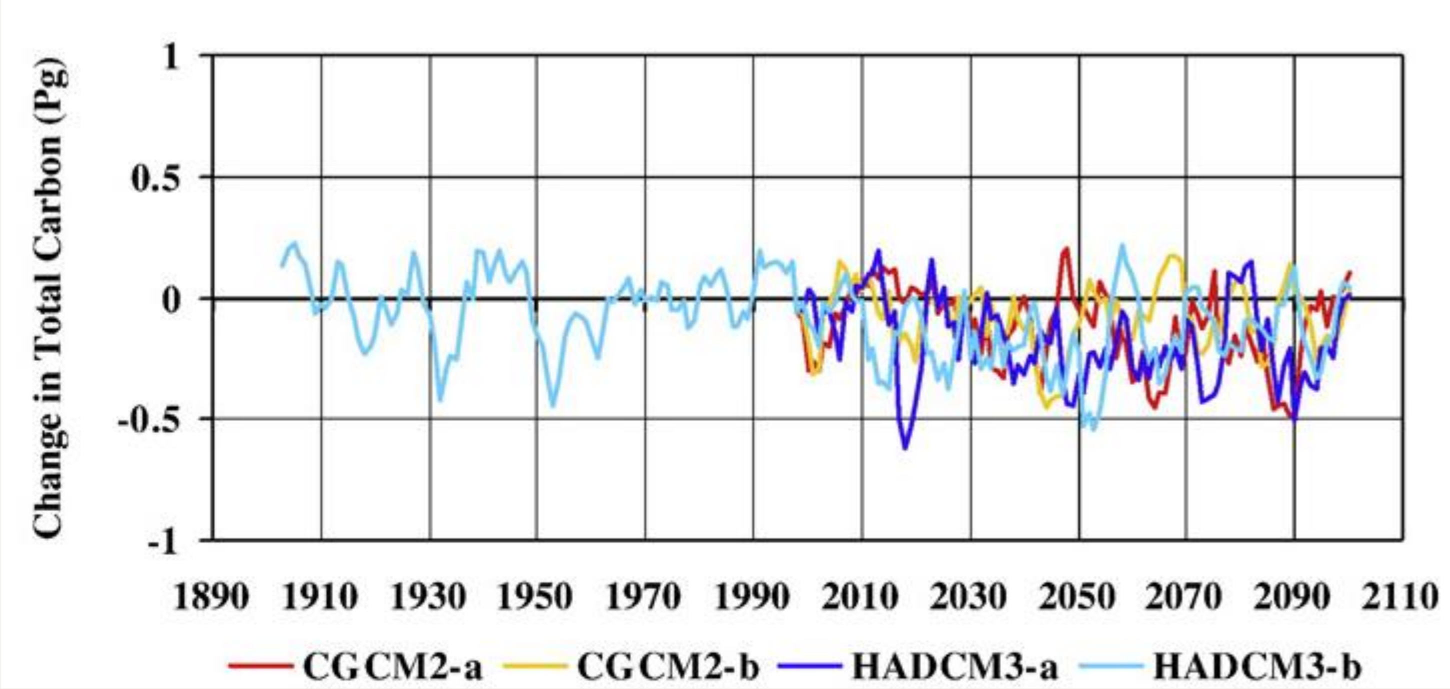
- *Reduction in total ecosystem carbon with climate change*.
  - Losses greatest in eastern US
  - Losses greater with more recent climate scenarios



Bachelet et al. (2008)

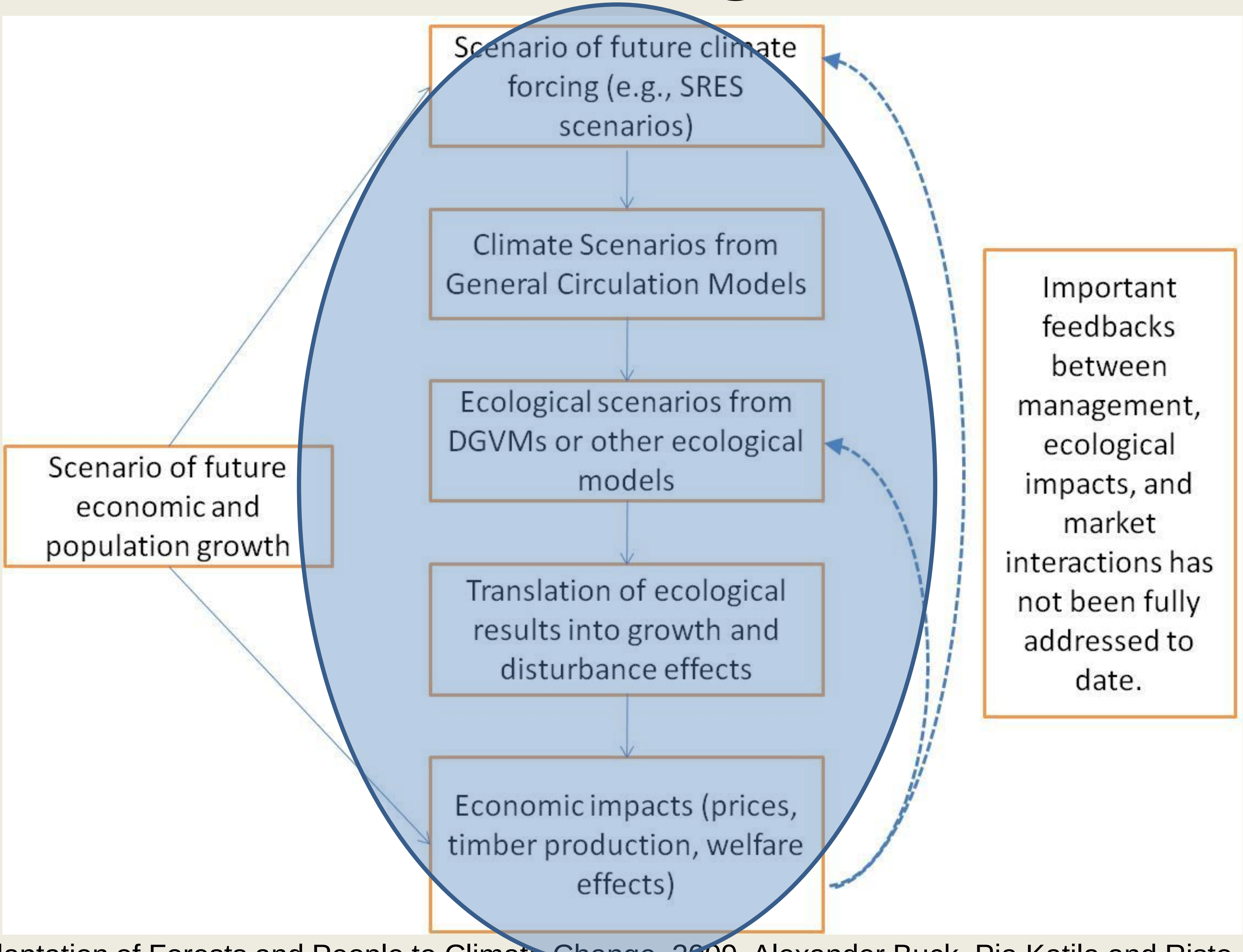
US Ecosystem Impacts

- *How big might the losses be?*
  - *Emissions of up to 500 million t C per year*
  - *Total loss over century of 10-20 billion t C.*



Bachelet et al. (2008)

Need to integrate…



Adaptation of Forests and People to Climate Change. 2009. Alexander Buck, Pia Katila and Risto Seppälä. (eds.). IUFRO World Series Volume 22. Helsinki. 224 p.

Summary: Timber market results to date

Region	Output		Producer Returns
	2000–2050	**2050–2100**	
North America	**-4%** to +10%	+12 to +16%	Decreases
Europe	**-4%** to +5%	+2 to +13%	Decreases
Russia	+2 to +6%	+7 to +18%	Decreases
South America	+10 to +20%	+20 to +50%	Increases
Aus./New Zealand	**-3** to +12%	**-10** to +30%	Decr. & Incr.
Africa	+5 to +14%	+17 to +31%	Increases
China	+10 to +11%	+26 to +29%	Increases
SE Asia	+4 to +10%	+14 to +30%	Increases

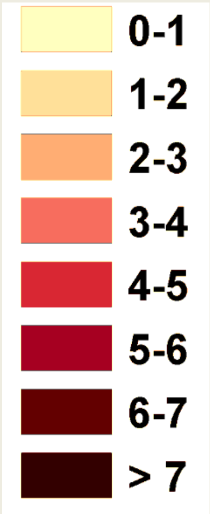
Alig et al. (2002), Irland et al. (2001), Joyce et al. (1995, 2001), Perez-Garcia et al. (1997, 2002), Sohngen et al. (2001), Sohngen and Mendelsohn (1998, 1999), Sohngen and Sedjo (2005); [2] Karjalainen et al. (2003), Nabuurs et al. (2002), Perez-Garcia et al. (2002), Sohngen et al. (2001) ; Lelyakin et al. (1997),

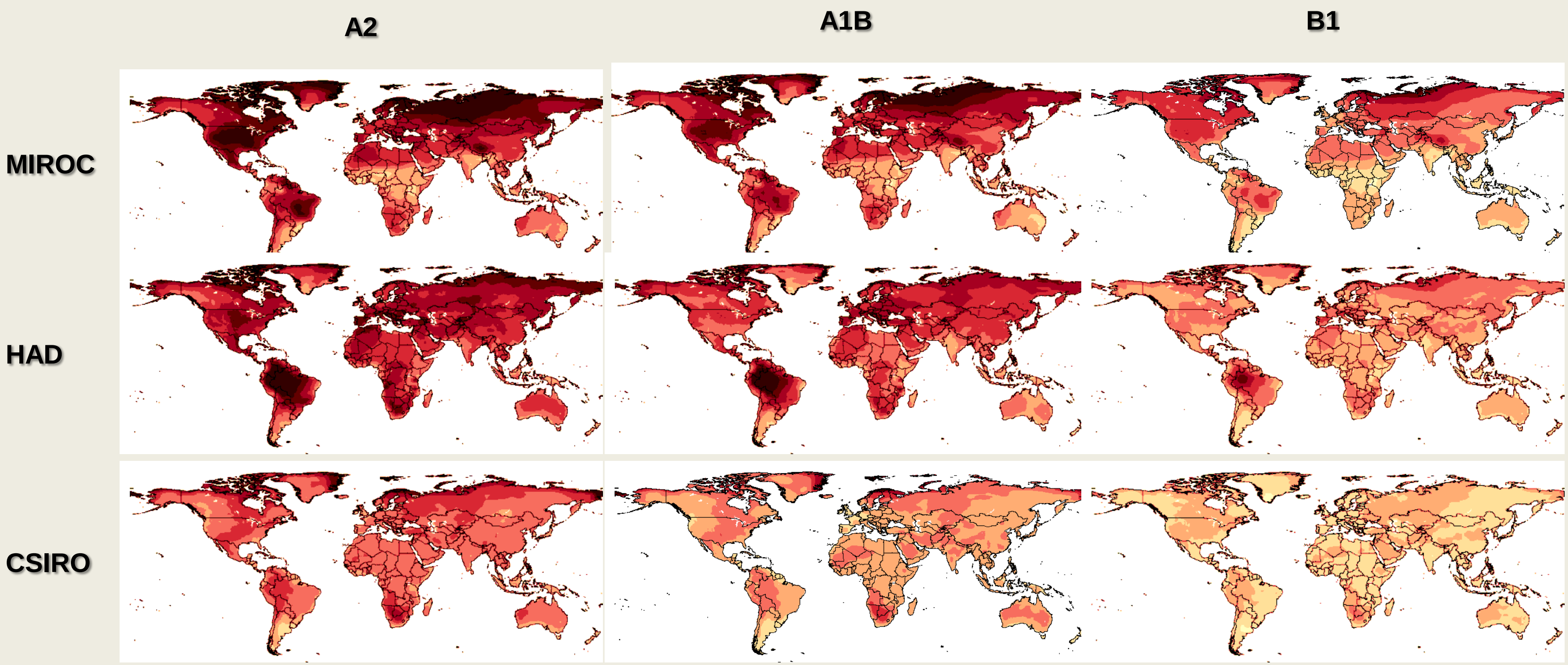
Adaptation of Forests and People to Climate Change. 2009. Alexander Buck, Pia Katila and Risto Seppälä. (eds.). IUFRO World Series Volume 22. Helsinki. 224 p.

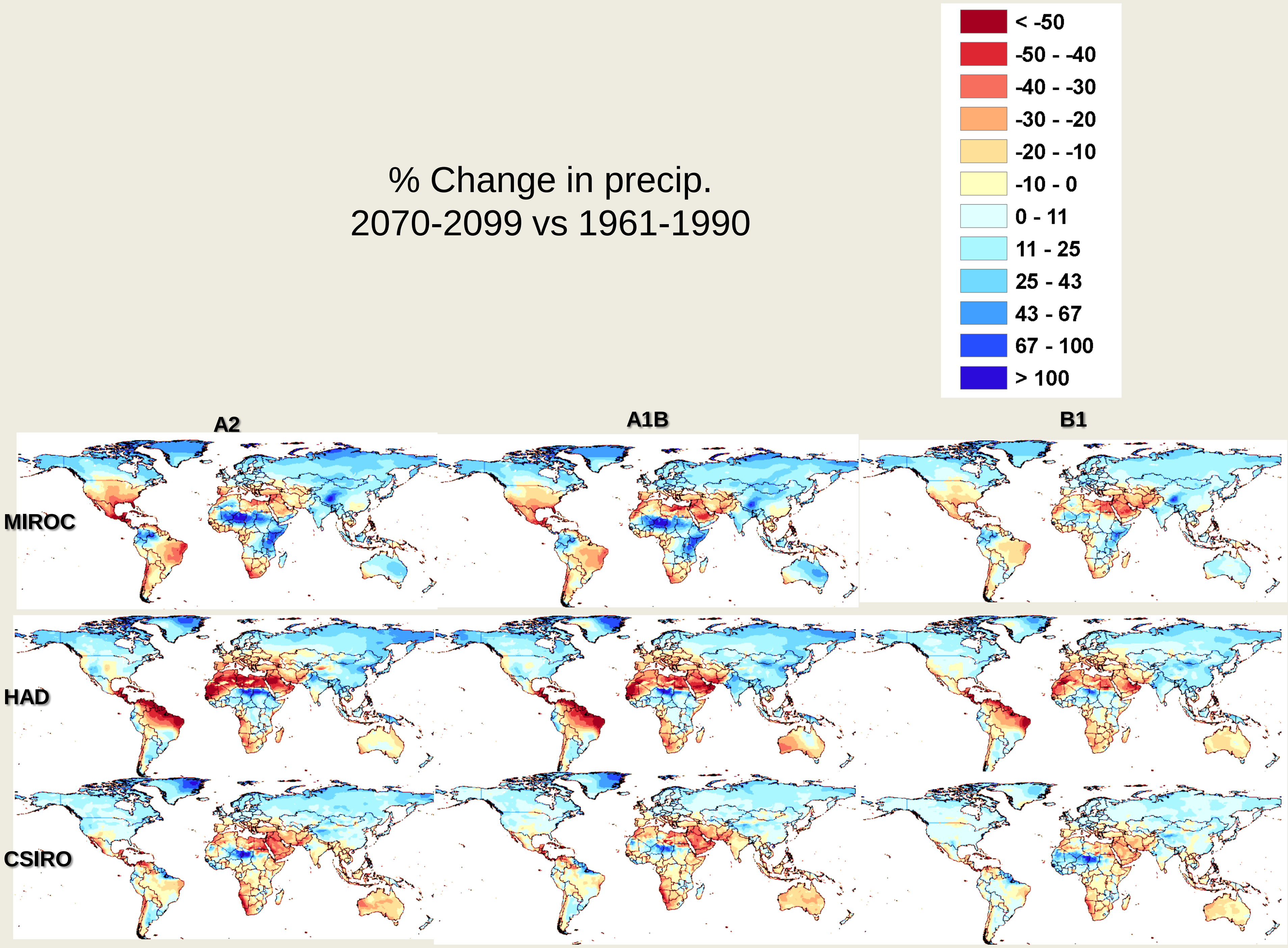
Updated Analysis

- Climate Change:
  - A2, A1b scenarios
  - CSIRO, Hadley, MIROC models
- Ecological Analysis: DGVM
  - MC1 model (MAPPS and Century Model)
- Economic Analysis:
  - Global Land Use Model (Sohngen and Mendelsohn, 2007)

Change in tmax
2070-2099 vs 1961-1990






% Change in precip.
2070-2099 vs 1961-1990
< -50
-50 - -40
-40 - -30
-30 - -20
-20 - -10
-10 - 0
0 - 11
11 - 25
25 - 43
43 - 67
67 - 100
> 100
A2
A1B
B1
MIROC
HAD
CSIRO

Approach to Economic Analysis

- Ecosystem Model (DGVM) provides information on
  - Shift in range for timber species
  - Natural disturbance losses (% stock burned)
  - Net primary productivity, net ecosystem productivity, and net biological productivity

- Data provided by DGVM
  - 0.5 degree grid cells for globe.
  - Annually to 2100.

Approach to Economic Analysis

Incorporate several factors

- Yield change is proportional to the change in NPP
- Yield changes captured as:

$$V_{A,t} = \sum_{a=1}^{A} \delta_t \dot{V}_{a,t}$$

- Stock losses due to burned area
- Stock losses captured as

$$X_{a+1,t+1} = \left(-\gamma_t\right) X_{a,t} - h_{a,t} + g_{a=1,t}$$

- Area suitable for trees changes
- Use maps of shifts in ecosystem types.

Adaptations Incorporated

- Manage existing stock by
  - changing rotations
  - Salvage
- Replant new species if growing and economic conditions warrant
- Manage future stock by
  - Changing rotations
  - Changing management & investments

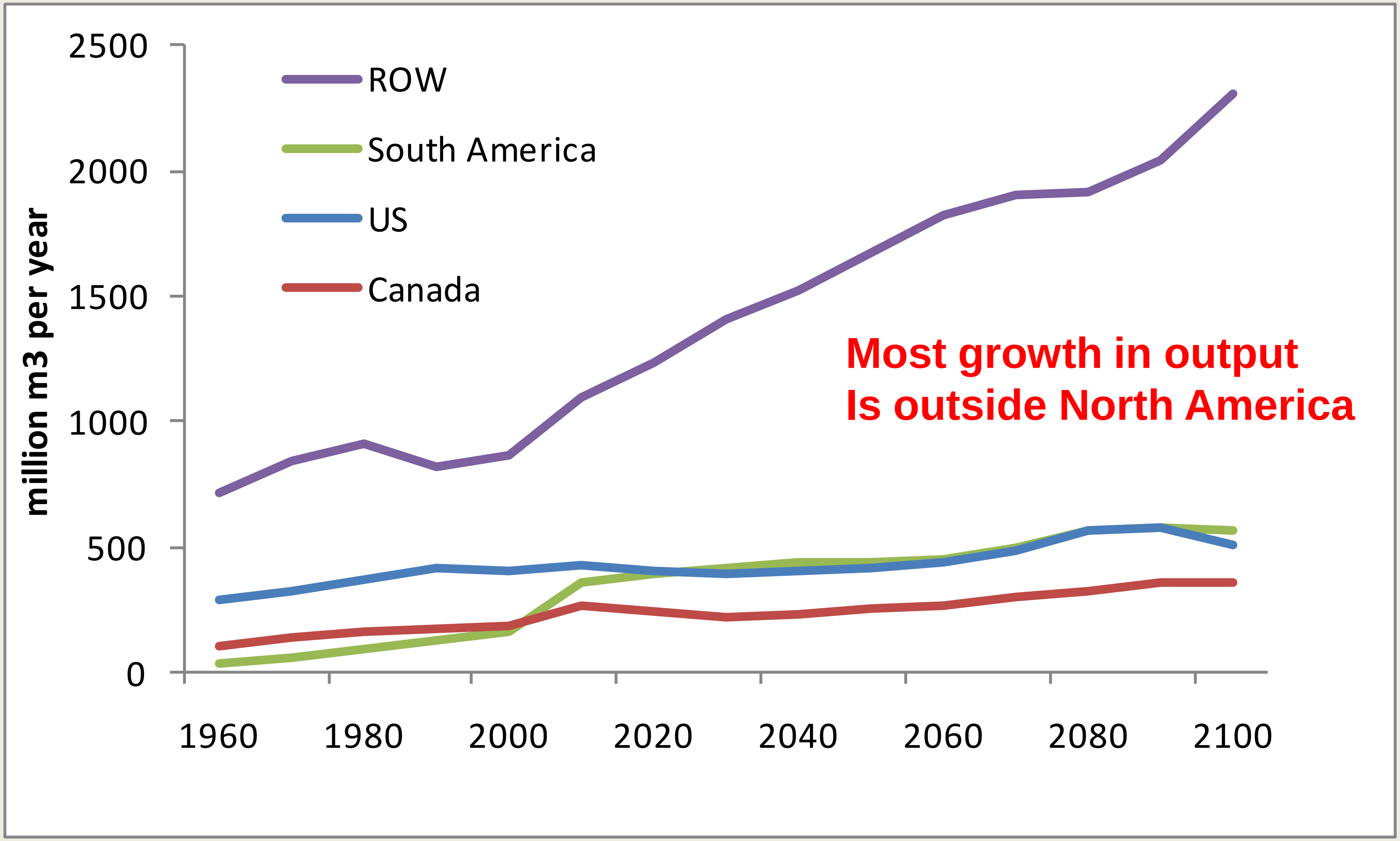
Some Results from Economic Analysis

- Climate Change strengthens current trends towards shorter rotations and production in subtropical regions.
  - South/Central America, Oceania, South Africa

	Age	m3/ha/yr	$/ha
US Southern Pine	30	4.8	$3,180
S. China mixed	50	1.8	$771
Canada Boreal SW	70	1.6	$288
Russia Boreal SW	100	1.0	$58
South Amer. Eucalypt	10	7.0	$8,453
Oceania SW	30	13.5	$7,937

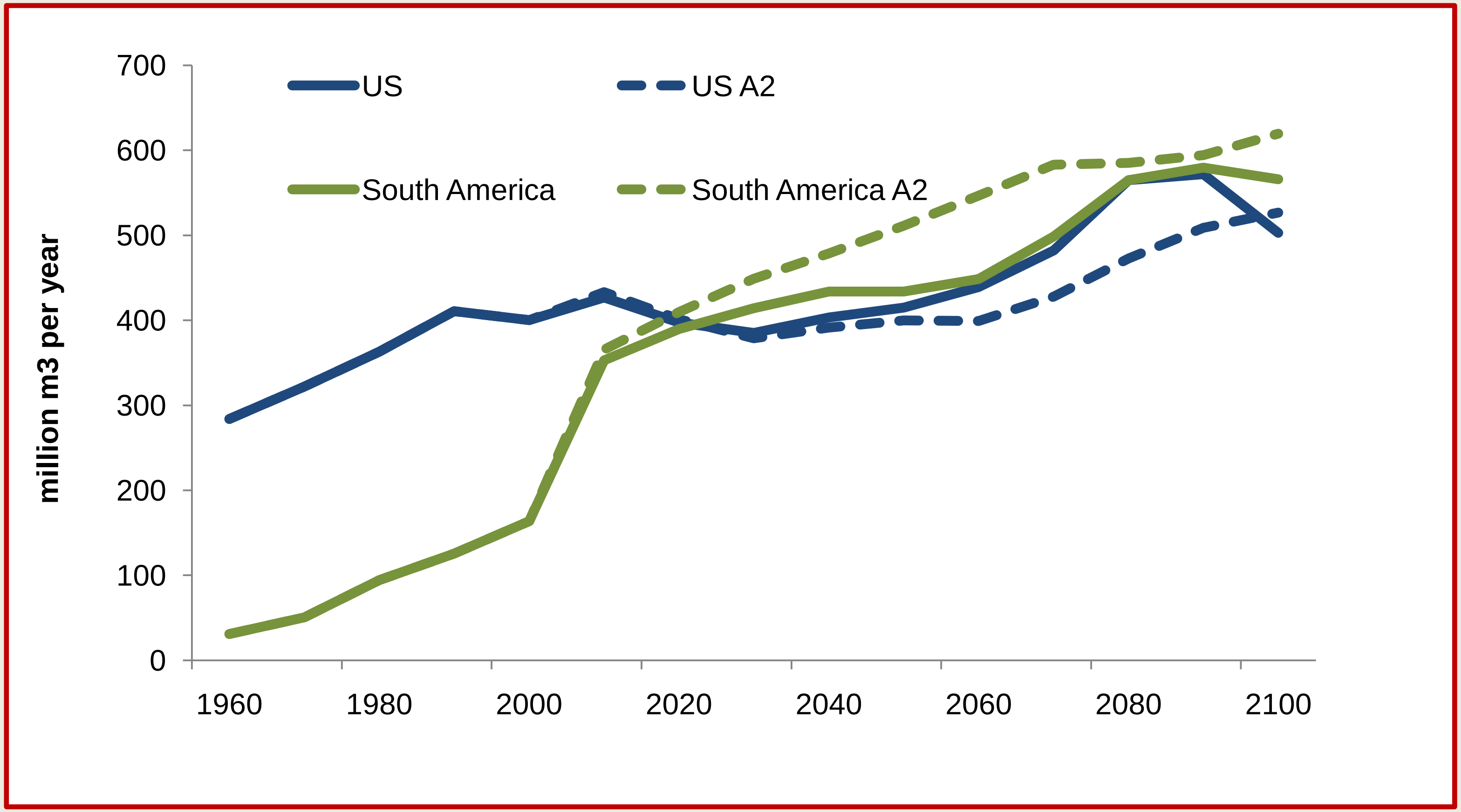
Source: Sohngen, 2010

Market Projections: No Climate Change



Market Projections with Climate Change

- South America gains some advantage under A2 for example

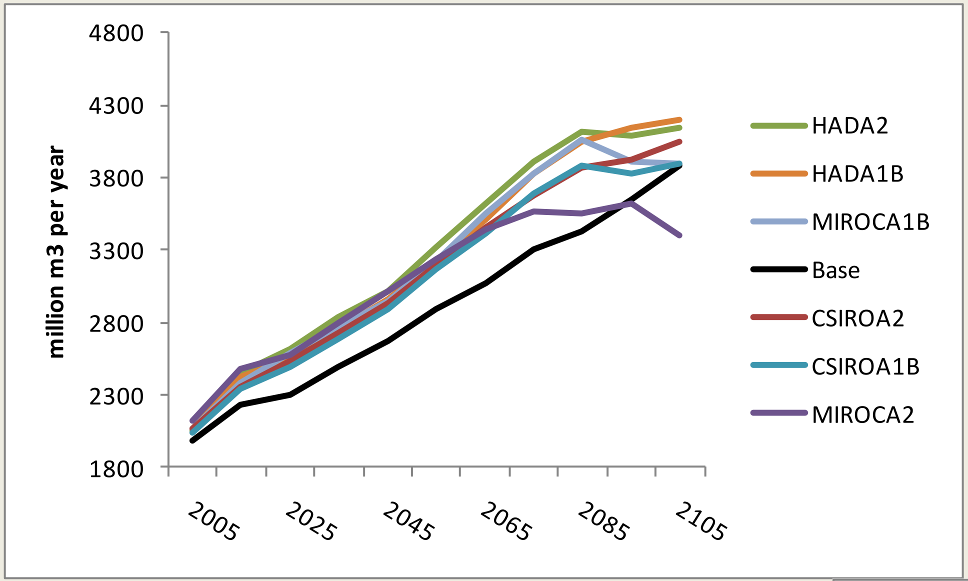


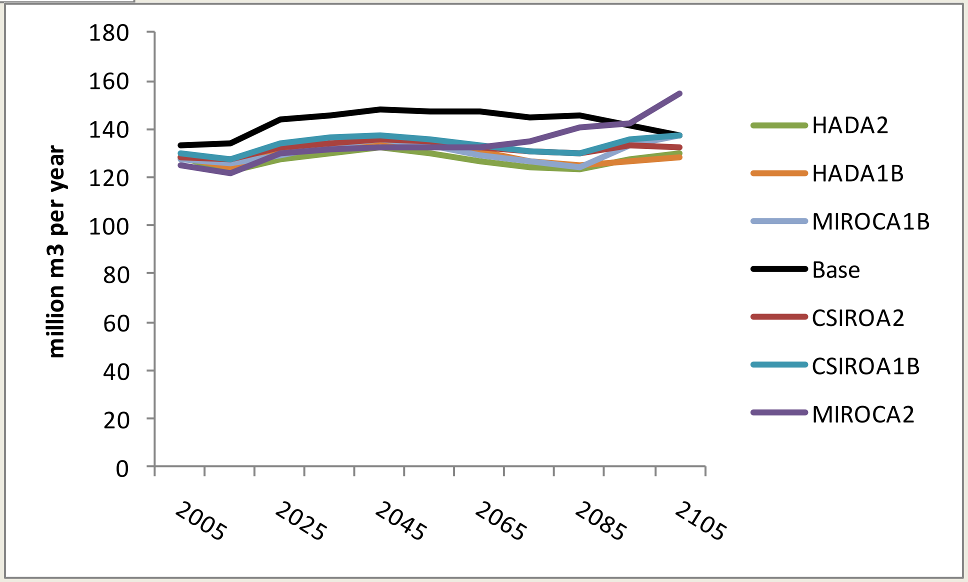
Some Results from Economic Analysis

- Climate Change strengthens current trends towards shorter rotations and production in subtropical regions.
  - South/Central America, Oceania, South Africa

- Global output rising and timber prices falling

Global Output and Prices fall by 5-15%





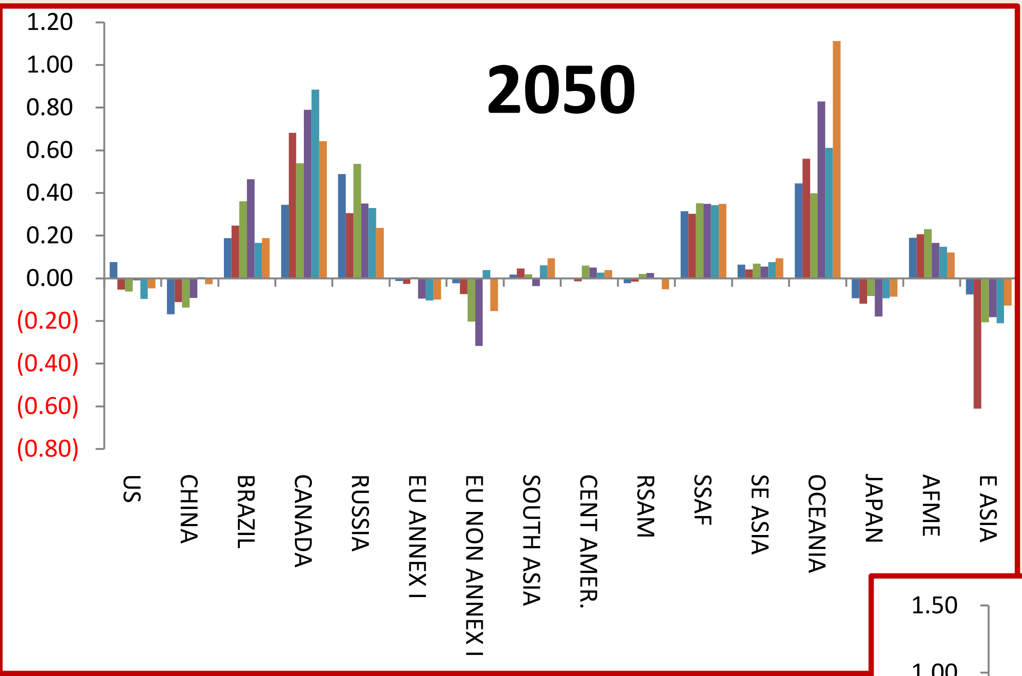
Some Results from Economic Analysis

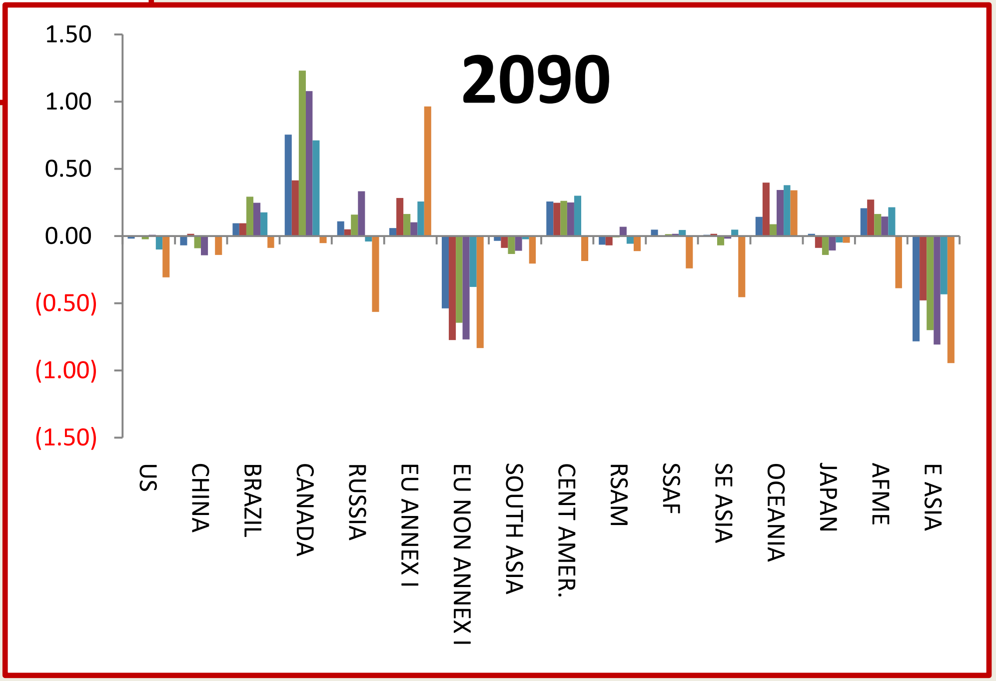
- Climate Change strengthens current trends towards shorter rotations and production in subtropical regions.
  - South/Central America, Oceania, South Africa

- Global output rising and timber prices falling

- Regional results suggest winners and losers, but dependent on climate scenarios.

Regional results variable





Some Results from Economic Analysis

- Climate Change strengthens current trends towards shorter rotations and production in subtropical regions.
  - South/Central America, Oceania, South Africa

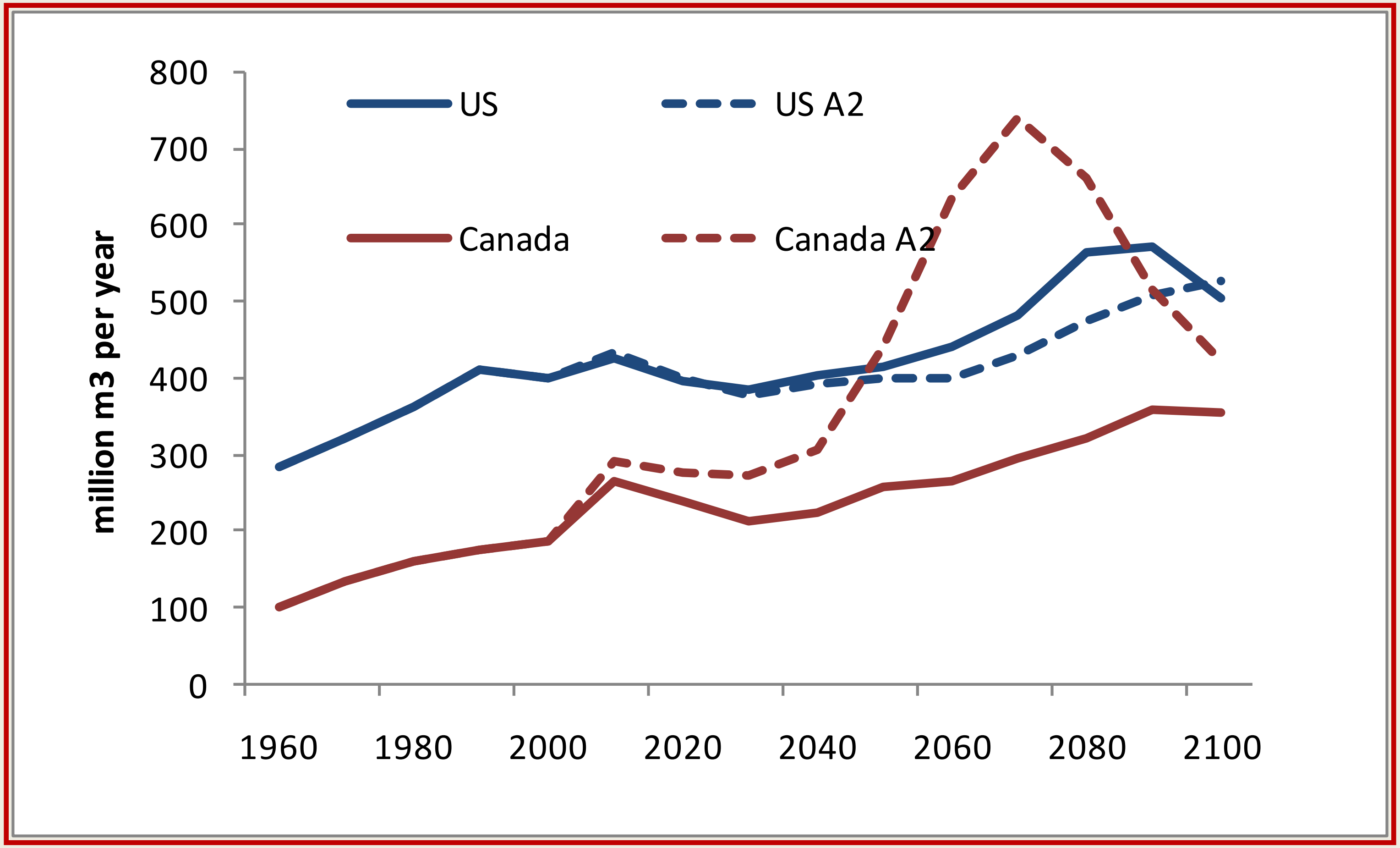
- Global output rising and timber prices falling

- Regional results suggest winners and losers, but dependent on climate scenarios.

- Management of forest stocks complicated by disturbance.
  - Large scale disturbances already influencing outputs in many regions (Mountain pine beetle in Canada, Forest fires in Russia, etc.).
  - Disturbance patterns expected to change with climate change.

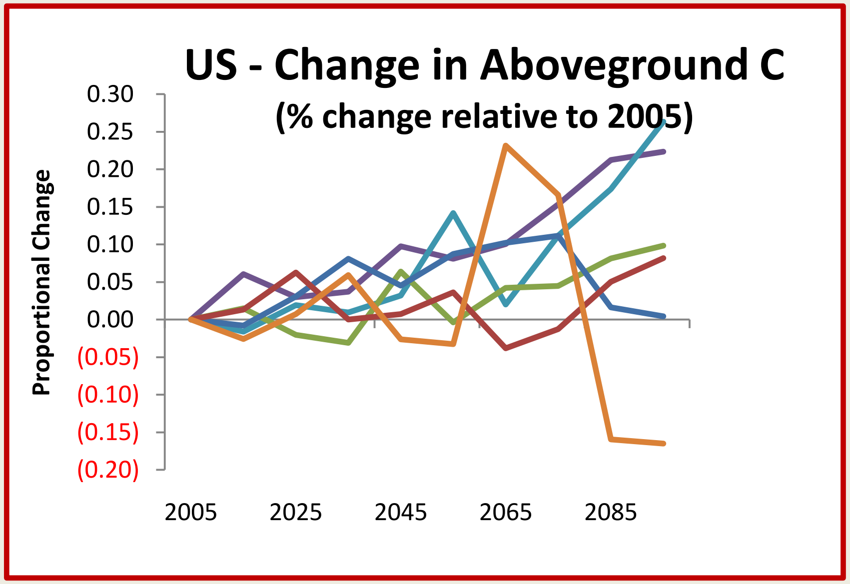
Disturbance and Adaptation.

- US and Canada example…

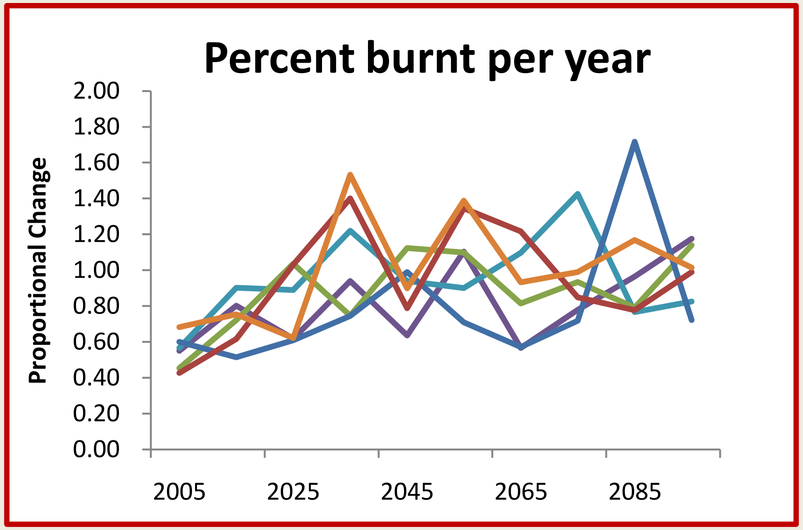


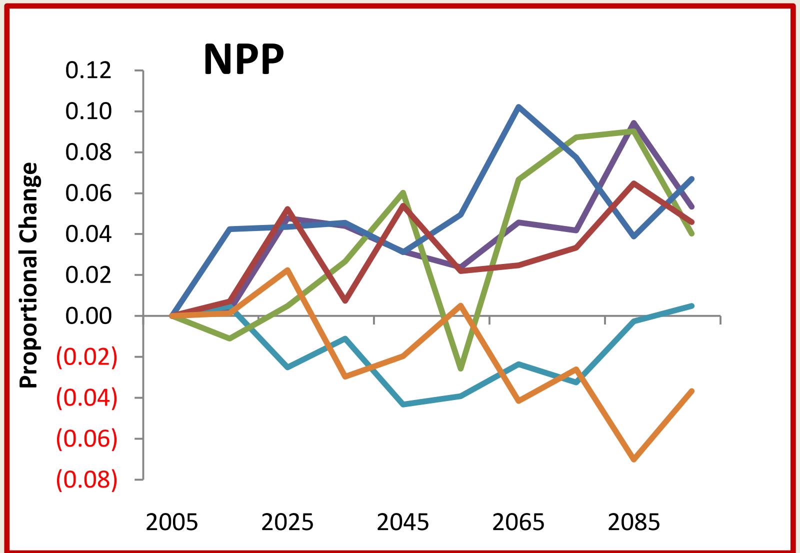
US: Ecosystem models projects a stock increase, but economic model projects a decrease in output…

- Aboveground C declines from the beginning.



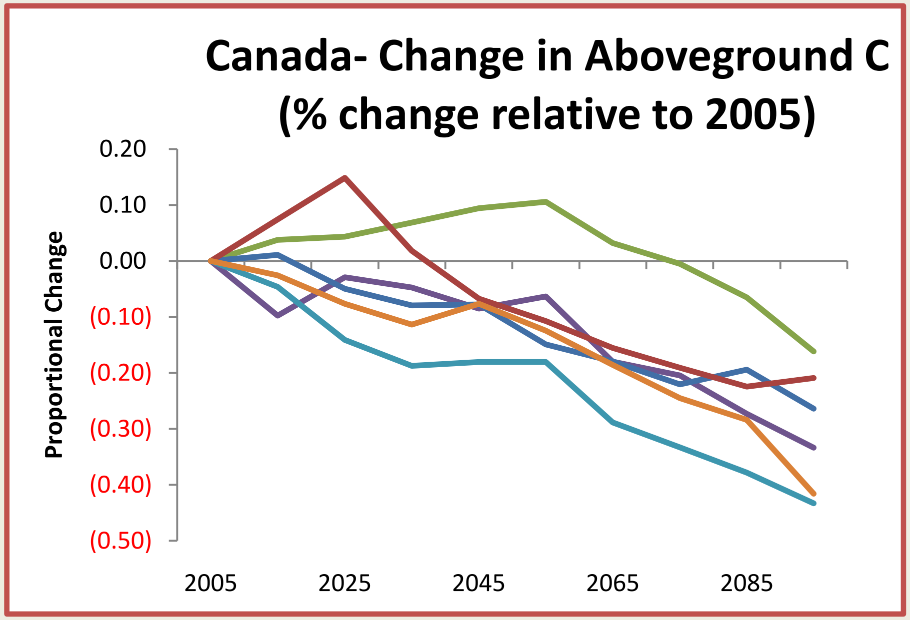
Forest rises a bit over time



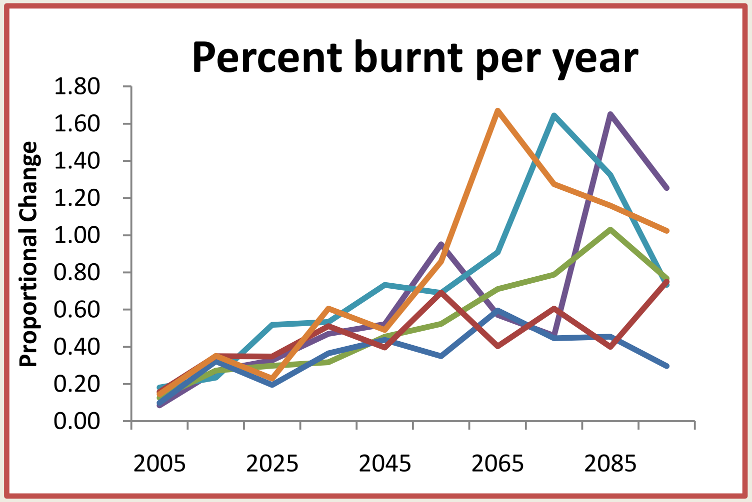


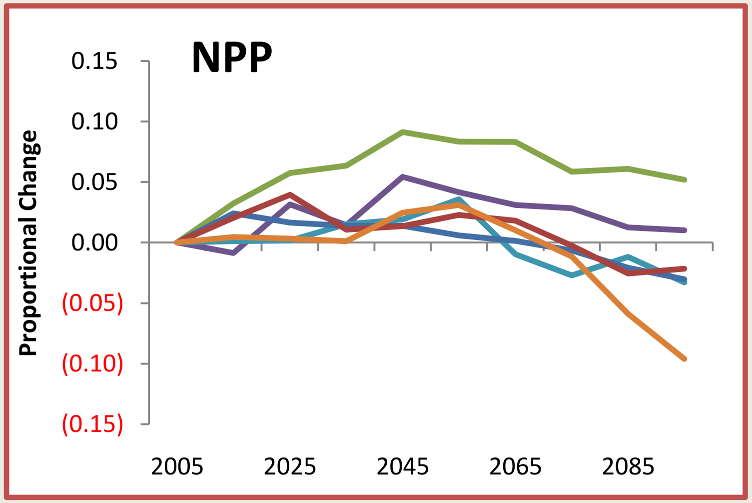
Canada: Ecosystem models project that stocks decline, but output increases

- Aboveground C declines from the beginning.



Forest burning builds over time





Summary and Key Limitations of Analysis

- Newer analysis has different scale of effects (smaller) and different regional implications.
- Economic analysis is evolving relatively slowly.
- Timber markets may not be most important demand on forestland in the future.
- Models are deterministic.
- Ecosystem models are calibrated without human influences.

Valuing the impacts of climate change on terrestrial ecosystem services

Alan Krupnick and David McLaughlin

Resources for the Future

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analyses

Capital Hilton, Washington, DC
January 27-28, 2011

Climate change is already having impacts on terrestrial ecosystem services, according to the IPCC, the Millennium Ecosystem Assessment and many other scientific reports, and such impacts are only expected to broaden and worsen as greenhouse gas emissions (GHGs) continue at their historic levels. To set appropriate policies for reducing GHG emissions, economists recommend the use of cost-benefit analysis to help decide on the appropriate stringency of policies, such as the size of a cap in a cap and trade system, the size of a carbon tax, or the stringency of a carbon fuels standard. To perform such analyses, the predominant approach has been to use integrated assessment models (IAMs), such as DICE. However, these models lack geographic specificity, must make hugely simplifying assumptions to capture the myriad effects caused by climate change and the welfare losses associated with them and not all components are based on public preferences. As such, there is a need for more targeted valuation studies to serve as further evidence about the willingness to pay (WTP) to reduce climate change.

The purpose of this brief paper is to sample and classify the literature valuing terrestrial ecosystem services and make some judgments about its usefulness to benefits analysis associated with climate change mitigation. As the valuation literature relevant to all types of terrestrial ecosystem services is enormous, this review is limited to studies valuing ecosystems, primarily nonuse values, which are likely to provide the largest aggregate values of any service one would label as based on terrestrial ecosystems (defined as land, river, and lake-based systems, excluding coastal and saltwater systems). With the emphasis on nonuse values, this paper focuses on stated preference studies, but also gives some attention to use values, and so includes revealed preference studies, such as those on recreation.

Classification of Ecological Endpoints Associated with Climate Change

Prior to the entrance of climate change into the valuation literature, this literature was mainly focused on ecological endpoints related to acid rain, ozone, land use change from urbanization, dam creation/removal, etc. This literature has relevance to climate change valuation, to be sure; yet it is inadequate for several reasons. First, there are novel types of ecosystem effects associated with climate change, such as shifts in the range of a species or subtle perturbations in ecosystem function related to incremental seasonal changes, such as from early alpine snowmelt. Second, climate change may effect geographical locations that have not been previously studied for valuation purposes. Third, climate change may produce larger scale effects (e.g., mass extinctions rather than one at a time). Fourth, the geographic scale of effects related to climate change, even if these effects are familiar, may be much larger, and the time phasing of these effects may take longer to begin and longer to reach a new equilibrium.

Fortunately, there are a variety of studies (e.g., IPCC report) that classify the full range of ecosystem damages associated with climate change. Unfortunately, these classifications involve much double-counting and contain endpoints that the public would be unable to value (Boyd and Krupnick, 2009) because they are inherently complex, require advanced scientific knowledge or are too far from their experience. It is beyond the scope of this paper to develop a complete classification system that includes only "valuation-relevant" endpoints and eliminates double counting, meaning that inputs to the processes affecting valuation-relevant endpoints, as well as the processes themselves, will not both be counted. Take for example an input and process such as submerged aquatic vegetation (SAV) (an input) and its provision of shelter to fish eggs and hatchlings (a process). Changes to the SAV affect its ability to provide shelter, which will ultimately affect the fish populations, the endpoint in this example. In the paper, we argue that people most easily and reliably value, and understand such endpoints and counting only them avoids double-counting.

For this literature review of valuation studies, we nevertheless needed some classification framework of relevant endpoints drawn from the scientific literature on climate change. These endpoints are not meant to be comprehensive. They appear along the top row of table 1, covering, first, recreation-related endpoints, such as fish populations, snow cover in ski areas, tourism, etc. Another category is related to "standard" nonuse values associated with species, which could include plant, bird, mammal and various aquatic species and cover changes in the population size, whether they are endangered or facing extinction and, looking across many species living interrelated in an ecosystem, measures of biodiversity. The term "standard" is used to indicate that endpoints under these subcategories are quite familiar to economists engaged in their valuation. The next set of categories is related to combinations of endpoints.

Three subcategories are highlighted that appear to be related to climate change, and other drivers of disturbance (e.g., land use or management changes). These include the changes in endpoints associated with wildfires and other events related to climate change, as well as aggregations of endpoints associated with climate change, such as large changes in biodiversity or mass extinctions. The last subcategory, "complete," is included to capture combinations of endpoints that include all the major categories of endpoint changes identified in the scientific literature (such as IPCC reports). The last category are endpoints that are unique to climate change (or at least long lasting changes in weather patterns), such as changes in the range of a species or ecosystem and perhaps some of the more subtle changes in an ecosystem associated with early snowmelt (e.g., changes in migratory patterns).[1] How one classifies endpoints of the same type that are affected over larger time periods or geographical area is arbitrary (are they "unique" or are they "standard"?). Not noted above, but essential to be mindful of, is the large degree of uncertainty associated with the magnitude and timing of climatic effects relative to the more modest uncertainty associated with, say, effects related to acid rain or ozone.

	Use Values	"Standard" Non-use values			Combinations			Unique endpoints	
	Recreation	Species			Disturbances	Multiple commodities	Complete	Events	
Study Design	e.g. Fishing, skiing, hunting, beach	Population change	Endangered or facing extinction	Decreased biodiversity	e.g. Wildfire, habitat loss, etc.	e.g., Biodiversity and habitat loss	All/Most relevant commodities	Range or ecosystem shift	Early snow melt impacts
1.) Top-down SP studies							X		
2.) Studies valuing ecosystem commodities from climate change	X	X	X	X	X	X		X	
3.) Studies transferring values to a climate change context	X	X	X	X		X		X	X
4.) Studies valuing relevant endpoints in a non-climate change context	X	X	X	X	X	X	X		

Table 1. Terrestrial Ecosystem Studies by study design and commodity: Classification of Reviewed Literature

Classification of the Valuation Literature

Table 1 contains a classification framework for the valuation literature that is somewhat unorthodox, in that it does not distinguish these studies by whether they are stated or revealed preference or meta-analysis, etc. The classification in the first column of table 1 relates to the credibility of cost-benefit analyses that would use this literature, beyond that of the methodology itself.

[1] Note that there are positive effects of climate change predicted for terrestrial ecosystems, such as faster tree growth (at least for a time). For simplicity, we ignore these in the discussion.

The top category covers studies that are designed to elicit WTP to avoid most, if not all, ecosystem-related changes expected from climate mitigation policy. The breadth of this "commodity" is so wide that only stated preference approaches can be used. The second category is studies valuing ecosystem endpoints in a climate change context. These are studies that were designed with the idea of valuing the types of ecosystem changes thought to be associated with climate change. Nevertheless, even if designed this way, they may not actually mention climate change. They are applicable to specific locations and types of terrestrial ecosystems, (e.g., the Murray River ecosystem or Colorado forests). The third category covers studies that have applied findings from studies valuing changes in terrestrial ecosystem services in a non-climate change context to estimated climate change impacts in a benefit transfer exercise. Before writing this paper, we were unaware whether many such studies existed and were surprised to learn that they do.

The final category (at the bottom of the first column) refers to studies valuing relevant endpoints in a non-climate change context. In this category is basically the entire ecosystem valuation literature that is motivated by non-climate change problems (e.g., acid rain). This literature provides values for a large number of the types of effects associated with climate change, e.g., species extinction, but might lack the scale or magnitude of effects associated with policies to mitigate climate change.

Turning to the interior of table 1, an "X" means that studies of one of the four types apply to the ecosystem endpoints indicated in the columns. By definition, the top category has an X only under "Complete" (even though their descriptions may be far from complete). And by definition, there are blank cells for the bottom row under the Complete and Unique columns.

The literature search that supports these X's was conducted using standard Google and Google Scholar searches, augmented by reference lists found in studies, as well as the Environmental Resource Valuation initiative (EVRI) database. We make no claim that this search was comprehensive. But, we feel we have a reasonable handle on the literature.

The surprise in the table is that there are X's in so many cells. Missing is benefit transfer studies for disturbances, but this may be occurring because of the limitations of our literature review.

Results from examining this literature

The following tentative findings emerge.

Timing. Because of the long lead times associated with the onset of some types of climate changes (or at least their most severe manifestations) and their potentially long duration, how preferences are related to this type of timing is important. While there are few studies upon which to make firm conclusions, in these it appears that the timing of the benefits of climate change mitigation doesn't seems to matter. That is, the longer term and the very distant future appear to be treated equally with respect to willingness to pay, implying very low or zero discount rates (Layton and Brown, 1999; Fleischer et al., 2006). These findings are consistent with the general tenor of the literature on temporal preferences. However, in our recent experience with focus groups comparing WTP for commodities offered in the near term (10 years) versus those offered further into the future (50 years), the latter timing creates scenario credibility problems. Respondents tend to believe that ecological improvements are less likely to occur the further into the future such changes are offered (Boyd and Krupnick, 2009). In a field study, statistically distinguishing such behavior from normal discounting would be very challenging. Some studies simply punt on the issue of communicating long-term changes and bring such changes into the near-future, or within the lifetime of the respondent, thereby overestimating WTP, assuming any positive discounting.

Scope sensitivity. With the profession moving more and more to choice experiment formats, scope sensitivity is now generally limited to showing that there is a positive and statistically significant coefficient on an attribute (i.e., that people are willing to pay statistically more for larger reductions in the same commodity). Such tests are run with panel data, where each respondent answers multiple choice questions, each with different levels of at least one attribute, including an associated cost.[2] This approach is less restrictive than the split sample set-up recommended by the NOAA Panel for contingent valuation studies.

Nevertheless, with this set-up, the studies reviewed here indicate that scope sensitivity is generally demonstrated, and further that there is decreasing marginal willingness to pay for increased number of species protected or for other metrics of increasing ecosystem services.

Uncertainty. Science has limited ability to predict both the future status quo effects from climate change and the ecosystem improvements arising off this baseline following a given GHG reduction. Thus, characterizing this scientific uncertainty in stated preference studies is important. Very few of the studies we reviewed explicitly vary the certainty with which mitigating actions will improve ecosystem qualities or quantities. Indeed, most appear to treat ecosystem improvements as if they would occur with certainty. In our focus group experience, admitting to uncertainty in ecosystem improvements from an intervention scenario results in respondents' questioning the science or the survey creator's understanding of the science, which itself results in lower or zero bids from some people. Statistically separating this type of "protest" bid from the normal behavior of being willing to pay less for a commodity that has a non-zero probability of being realized (relative to the same commodity offered with certainty) is another major challenge.

A Tempting Option. The studies classified as "top-down" (see row one of table 1) are a very tempting alternative to the messy and almost impossible business of doing very detailed valuation studies in many habitats and using benefit transfer to fill in the rest. The existing literature in this category covers studies that ask for WTP for reducing greenhouse gas emissions

[2] Occasionally, studies bundle several terrestrial ecosystem services to account for tradeoffs between valuing different ecosystem services. (Riera et al., 2007)

and avoiding the consequences of climate change. Some studies ask for the WTP to offset air travel (Brouwer et al., 2008), or for taking mitigation actions (Akter and Bennet, 2008), or to reduce dependence on foreign oil and carbon emissions (Li et al., 2009), to implement the Kyoto Protocol (Berrens et al., 2004), or more explicitly (Berk and Fovell (1999)) to prevent significant climate changes. Cameron (2005) used a convenience sample of college students and found that respondents who are more certain about a given increase in average temperatures have higher WTP to prevent such an increase. In line with these results, Viscusi and Zeckhauser (2005) and Akter and Bennett (2008) also found that people who find global warming to be more likely also have higher WTP. Hence, as might be expected, one important explanatory factor for how much individuals are willing to pay for mitigating climate change is if they believe in climate change.

Details on a Broad Climate Mitigation Valuation Study (Carlsson et al, 2010)

In a survey performed by Carlsson et al. (2010), respondents were told that the magnitude of future temperature increases will depend on the amount of future global CO2 emissions; specifically, if CO2 emissions are reduced from current emission levels by 30%, 60%, and 85% respectively, then the temperature increase will be limited to 4°F, 3°F, or 2°F. If the world instead does not reduce emissions but continues with "business as usual" (BAU), the temperature is expected to increase by more than 4°F in 2050. The survey explained, based on information from the IPCC, that this would most likely correspond to large changes in the global ecosystem and most countries would be negatively affected. An information screen (figure 1) summarized these effect of temperature increases on harvests, increased flooding and storms, and ecosystem effects by the year 2050.

Global emissions reduction	**85% reduction**	**60% reduction**	**30% reduction**
Temperature increase	2°F increase	3°F increase	4°F increase
Harvest	Harvests in countries near the equator decrease by 4-6%. Harvests in countries in the northern hemisphere increase by 1–3%.	Harvests in countries near the equator decrease by 10–12%. Harvests in countries in the northern hemisphere are unaffected.	Harvests in countries near the equator decrease by 14–16%. Harvests in the northern hemisphere decrease by 0–2%.
Increased flooding and storms	Small tropical islands and lowland countries (for example, Bangladesh) experience increased flooding and storms.	Additional low-lying areas in the Americas, Asia, and Africa experience increased flooding and storms.	Populous cities face increased flood risks from rivers and ocean storms. Existence of small island countries is threatened.
Threatened ecosystems	Sensitive ecosystems, such as coral reefs and the Arctic, are threatened.	Most coral reefs die. Additional sensitive ecosystems and species around the world are threatened.	Sensitive and less-sensitive ecosystems and species around the world are threatened.

Figure 1. Global Emissions Reduction, Temperature Increase and Its Effects as Presented to Survey Respondents in Carlsson et al. (2010)

This survey screen is a good example of responses to the above key issues (and others). Overall, the "commodities" being valued encompass both ecosystem effects as well as harvests and storms/flooding, with some specific species – coral reefs – and specific locations called out. These choices are in line with the IPCC's "most likely" predictions. Timing of the effects of global warming is set at 2050, a simplification and forward telescoping of the path of effects we might see. Uncertainty is handled obliquely by providing ranges of likely effects (e.g., 1-3 percent reduction in harvests) in the table, and using words like "most likely" in the text. However, in the information screen above (which also doubles -- with slight modifications – as the choice experiment screen) declarative phrases are used, e.g., "most coral reefs die", as opposed to using qualifiers on the verb, such as "may die." These choices were guided by focus group feedback. Probably the most subtle approach to uncertainty is with description (or lack of description) of the future baseline, of which is said only that temperature change of greater than 4 degrees F "…would most likely correspond to large changes in the global ecosystem and most countries would be negatively affected" (Carlsson et al., 2010). This decision to so vaguely define the baseline also was made in response to focus group feedback and the difficulty of concisely describing widespread and possibly dramatic effects. Finally, the survey passed scope sensitivity, although as designed the test was of internal (rather than external) scope sensitivity.

In any event, the survey yielded many interesting results. Carlsson et al. (2010) found that a large majority of the respondents in *all three* countries believe the mean global temperature has increased over the last 100 years and that humans are responsible for the increase. Americans, however, believe less in both aspects compared to Chinese and Swedes. A larger share of Americans appears to be pessimistic; they believe that we cannot do anything to stop climate change. Carlsson et al. (2010) also found that Sweden has the highest WTP for reduction of CO_2 and China has the lowest. In going from a 30% reduction in GHGs to 60%, for instance, the Swedes were willing to pay $20 per household month, while the U.S. sample was willing to pay $10 and the Chinese $4. Interestingly, when the WTP is measured as the share of household income, the willingness to pay is about the same for American and Chinese sample, but much higher for the Swedes.

The findings from Carlsson et al. (2010) show that the U.S. population contains a far larger percentage of climate skeptics (24 percent by one metric) than in Sweden or even China (both around 5-6 percent). With such a large fraction of the population thinking this way, survey researchers must be concerned that WTP for ecosystem improvements themselves, irrespective of the cause, not be biased downwards simply because respondents discount the link between climate change and the ecosystem changes being offered or biased upwards through double-counting due to the respondent's inclusion of joint benefits (e.g., human health) in their WTP.

This situation is not unlike that faced by researchers seeking values for reducing mortality risks from air pollution. Best practice is to avoid conveying the cause of reducing such risks (e.g., reducing particulate emissions) because such reductions carry with them cognitive linkages to other types of improvements (say in morbidity or visibility or materials damages), which tend to inflate WTP, or feelings leading to scenario rejection or downward bias. The most common of these feelings in our focus group work has been that respondents should not be responsible or pay for reductions in air pollution because it is "industry's fault." Both of these problems – linkage bias and scenario rejection – are likely to be present to an even greater extent in climate change valuation studies relative to valuation studies for conventional air pollutants.

This situation could lead to more efforts, such as that from MacDonald et al. (2010) on the Murray River region in Australia, where climate change is not even mentioned as a causal driver of change, and mitigation of GHGs is not mentioned as a motivator for ecosystem improvements. It remains to be determined whether plausible alternative stories can be constructed for delivering such widespread and large improvements in ecosystems as are thought to be realizable from large GHG reductions. If they can't, perhaps the best approach would be to include questions to determine whether or to what degree a respondent is a climate skeptic and to adjust for this statistically or through their exclusion. To do so, however, risks overvaluing the improvements, as legitimate zeros or low values may be excluded.

Conclusion

Is this literature ready for prime time, i.e., to be used to help develop and justify a social cost of carbon? A top level response is that, with the pervasiveness of the effects of global warming on all types of natural and human systems, and given the interconnectedness of those systems, it seems too reductionist to focus on valuation of changes to specific resources or systems, in this case terrestrial ecosystems. That is, the value of slowing climate change needs to be estimated from a holistic perspective. To do so, the only possible way to go is with the top-down studies like those defined in the first row of table 1, recognizing that these studies can never provide the detail and the preciseness of commodity definition that is desirable in, say, natural resource damage assessments. However we must ask ourselves as a society if we are willing to trade off precision for comprehensiveness/breadth.

What is the alternative? In our view, the vast literature simply valuing ecosystem services is not largely motivated or directly applicable to climate change. And use of these studies in benefits transfers therefore involves huge assumptions (e.g., about how much two extinctions are worth avoiding relative to one) and, even then, there will be gaps in geographic coverage. On a more hopeful note, there are an increasing number of ecosystem valuation studies motivated by climate change that have the right scale and type of commodities being valued (see table 1, row 2). Yet, such studies are invariably place-based and draw relatively tight, rather than porous boundaries between the ecosystem of interest and its linkages to other systems. Thus, one will not be able to easily aggregate such studies, properly account for overlaps and gaps and eventually come out with a cost of carbon. However, examining such studies one at a time and drawing insights out of them may both inform the design of information treatments for the studies, like those found in the first row of our classification, and lead to a more qualitative/judgmental basis for settling on a cost of carbon number.

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Valuing the impacts of climate change on terrestrial ecosystem services

Alan Krupnick

Resources for the Future

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analyses

Capital Hilton, Washington, DC

January 27-28, 2011

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Definitions and scope

- Terrestrial: everything but coastal and ocean
- Here, my focus is on the squishiest of ecosystem services: non-use values
  - Stated preference (survey-based) studies. A low WTP per person goes a long way!
- Endpoints: biophysical effects estimated by natural scientists that are used as startpoints in valuation studies

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The task

Based on climate drivers

Based on preferences -- WTP

A million of them. Which to choose?

$$SCC_T = \text{Unit values} * \Delta\ \text{Endpoint}$$

Need to match
- Natural scientists respond to their drivers
- Economists have no consensus on what to measure ➔ no harmonization, huge variance

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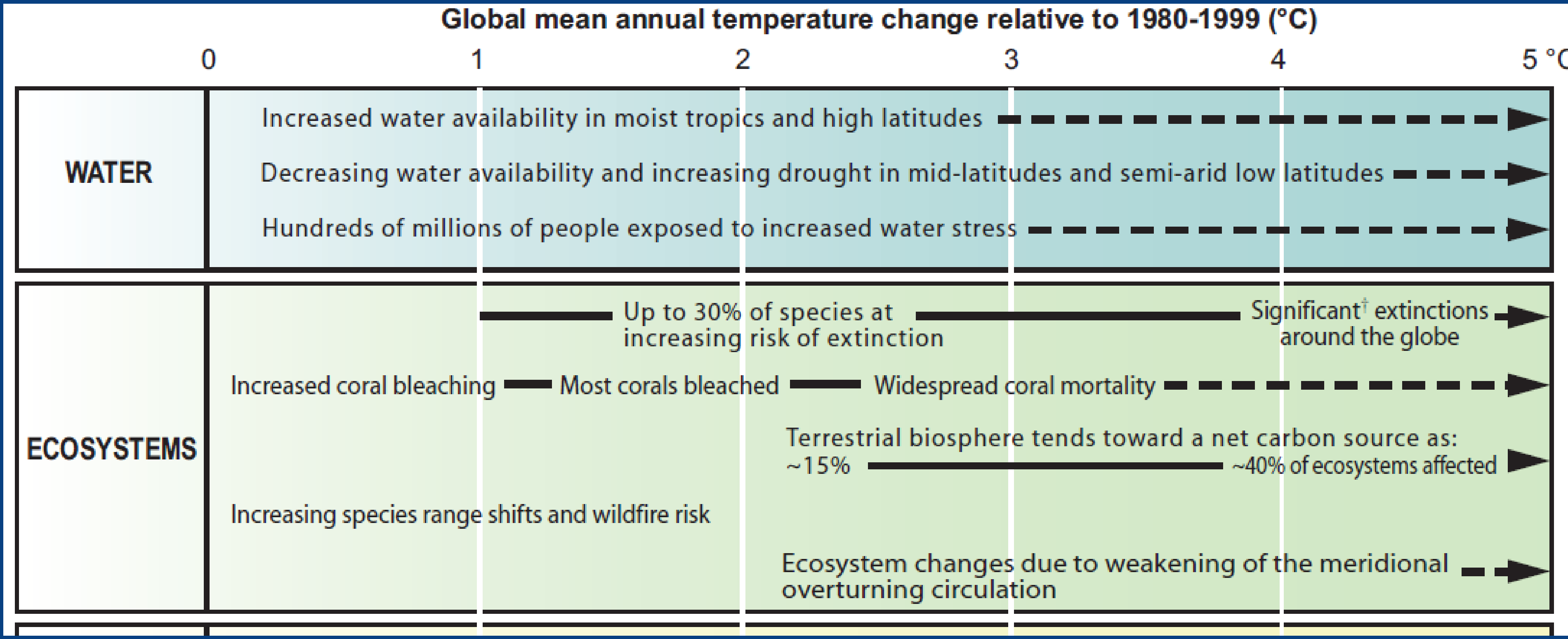
Issues

- Does the natural science examine the appropriate endpoints and build the appropriate functional relationships to link back to climate variables and interventions?
- Are those endpoints valued? Credibly valued? Are the valuation studies comprehensive enough?

ENDPOINTS AT ISSUE:

IPCC



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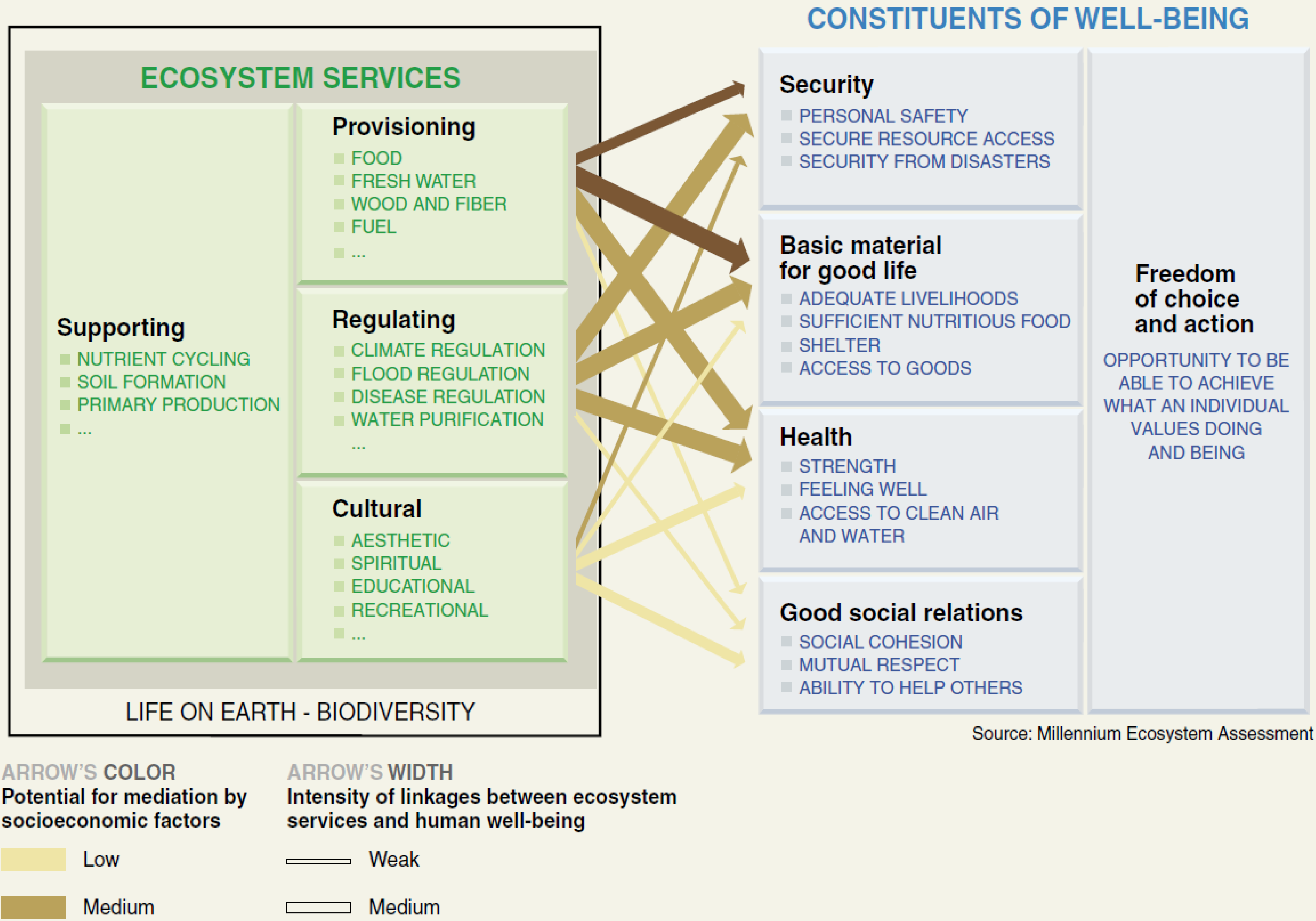

Source: Millennium Ecosystem Assessment

Ecological Production Theory

- Same thing
  - Biophysical inputs
  - Transformed via natural processes into
  - Biophysical outputs

$Q_i = f\,(I_{i1}, I_{i2}, \ldots)$

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Production Function Error

- What is the value of "more acres of eagle habitat?"
- Need to know two things

  (1) The value you place on eagle abundance

  (2) The production function that translates eagle habitat into eagles

Respondents will intuit a relationship
But won't know magnitude

Startpoint Categories for Climate Change

- Use (e.g., fish populations)
- “Standard” non-use (e.g., single species population change, extinction)
- Combinations associated with events (e.g., wildfires) or broad scale changes (e.g., desertification)
- Novel changes (e.g., range shift, mass extinctions)

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Valuation studies classification

- Studies valuing relevant commodities in non-climate context
- Studies transferring these values to a climate change context
- Studies valuing relevant commodities in a climate change context
- Stated preference top-down studies

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Standard Endpoints

Please vote:

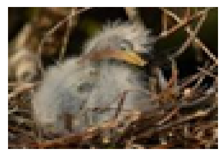
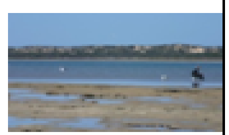
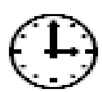
The following vote offers a choice between *No Program* and *an Improvement Program option*. The **future conditions** of the SAM Region by 2019 for each choice are summarized below. What is your vote?

	No Program	Improvement Program
Streams and fish	**150,000** healthy streams; **150,000** streams of concern. Up to **6** species of fish harmed in streams of concern.	**20%** of all streams (**60,000** streams of concern) will improve and be stocked with these fish.
Bird populations	Three songbird species are **65%** of what they once were.	Three songbird species improve to **85%** of what they once were.
Forests	**3%** (**780,000** acres) of SAM Region has damage to red spruce and sugar maple trees.	**1%** of SAM Region (**260,000** acres) improves
Your additional state tax	**$0**	**$500** in total (**$50** per year for 10 years)

Your Vote?	❐	❐

Murray River Watershed

Boyle et al, 2010

		Option A Current Condition	**Option B**	**Option C**
Native fish		10% of original population	20% of original population	40% of original population
Healthy Riverside Vegetation and Wetlands		50% of original area *178,000 ha*	60% of original area *200,000 ha*	70% of original area 240,000 ha
Frequency of Waterbird breeding		Every 10 years	Every 8 years	Every 3 years
Coorong and Lower Lakes		Coorong declining rapidly	Coorong healthy	Coorong declining rapidly
Time until improvement occurs			5 years	20 years
Household cost *per year for 10 years*	$	$0	$100	$250

Fleischer and Sternberg, Ecol. Econ, 2006

Program 1 No action	Program 2 Forestation is used to slow down greenhouse effect	Program 3 Reduction in the use of greenhouse gases	Program 4 Forestation and greenhouse-gas reduction	Program 5 Drastic reduction in greenhouse gases
Landscape in the Galilee[a] will become arid, also loss of plant life will occur	Landscape in the Galilee[a] will become semiarid	Landscape in the Galilee[a] will become semiarid	Landscape in the Galilee[a] will have less plant life	Landscape in the Galilee[a] will not change
$0 per month	$7.5 per month	$7.5 per month	$15 per month	$20 per month
Mesic Mediterranean 	Mesic Mediterranean 	Mesic Mediterranean 	Mesic Mediterranean 	Mesic Mediterranean 
Arid 	Semiarid 	Semiarid 	Mediterranean 	

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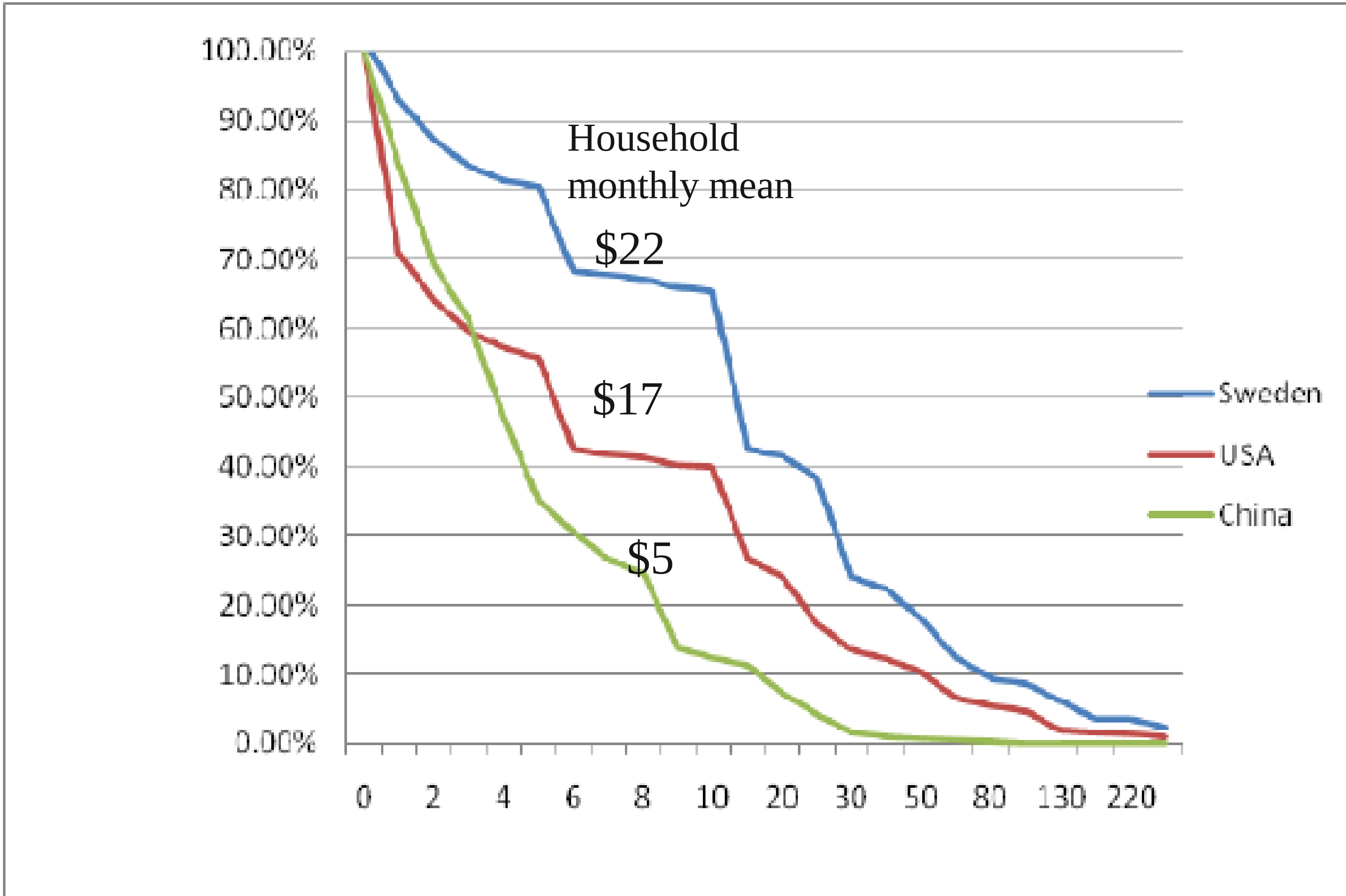
Table 1. Global Emission Reduction, Temperature Increase, and Its Effects as Presented to Survey Respondents

Global emissions reduction	**85% reduction**	**60% reduction**	**30% reduction**
Temperature increase	2°F increase	3°F increase	4°F increase
Harvest	Harvests in countries near the equator decrease by 4-6%. Harvests in countries in the northern hemisphere increase by 1–3%.	Harvests in countries near the equator decrease by 10–12%. Harvests in countries in the northern hemisphere are unaffected.	Harvests in countries near the equator decrease by 14–16%. Harvests in the northern hemisphere decrease by 0–2%.
Increased flooding and storms	Small tropical islands and lowland countries (for example, Bangladesh) experience increased flooding and storms.	Additional low-lying areas in the Americas, Asia, and Africa experience increased flooding and storms.	Populous cities face increased flood risks from rivers and ocean storms. Existence of small island countries is threatened.
Threatened ecosystems	Sensitive ecosystems, such as coral reefs and the Arctic, are threatened.	Most coral reefs die. Additional sensitive ecosystems and species around the world are threatened.	Sensitive and less-sensitive ecosystems and species around the world are threatened.

Figure 1. Distribution of WTP Responses for 30% Greenhouse Gas Reduction



Usefulness of literature

- Existing "non-climate" studies – useful but limited
- BT with above studies: artificial and assumption-based
- Climate-driven studies: useful, growing literature, but will always be "patchy"

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Top-level studies as tempting option

- Broad coverage of endpoints and locations
- But highly imprecise commodity definitions and scenarios
- What's the alternative?
  - Perhaps benefits transfers from well-done climate-based valuation studies.

Classification of the Valuation Literature

	Use Values	"Standard" Non-use values			Combinations			Unique endpoints	
	Recreation	Species			Disturbances	Multiple commodities	Complete	Events	
Study Design	e.g. Fishing, skiing, hunting, beach	Population change	Endangered or facing extinction	Decreased biodiversity	e.g. Wildfires	e.g. Biodiversity and mass extinctions	All/Most relevant commodities	Range or ecosystem shift	Early snow melt impacts
1.) Top-down SP studies							X		
2.) Studies valuing ecosystem commodities from climate change	X	X	X	X	X	X		X	
3.) Studies transferring values to a climate change context	X	X	X	X		X		X	X
4.) Studies valuing relevant endpoints in a non-climate change context	X	X	X	X	X	X	X		

Results

- Most cells filled in → a lot of studies to work with for meta-analyses and benefit-transfer

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Spatial Scale

- Studies range widely in spatial scales
- Desire for specificity to enhance credibility:
  - "tangible" commodities and convincing scenarios

Scope Sensitivity

- WTP more for avoiding larger damages/gaining larger benefits
- Decreasing marginal returns

Timing

- Timing of benefits doesn't seem to matter much
- Low discount rates
- Not addressed by many studies

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Uncertainty

- Most assume certainty
- Very few vary uncertainty
- Admitting to uncertainty may induce protest bids
  - Rejection of science or survey
  - Difficult to sort out from "legitimate" responses

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What is needed

- From Ecologists: Endpoints that match valuation startpoints and have functional relationships with climate drivers
- From Economists: consensus approach to classifying endpoints to be used as valuation startpoints

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Final thoughts

- Should surveys mention climate change?
  - Climate skeptics
- How to admit uncertainties in surveys?
- Need holistic valuation estimates (more than just terrestrial ecosystem effects) – no presumption of additivity ➔ top down SP studies? Or top down SP studies for non-market ES only?

RESOURCES FOR THE FUTURE

Energy System Impacts of Climate Change: An Overview

for
EPA/DOE Workshop on Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis
Research on Climate Change Impacts and Associated Economic Damages
Washington DC
January 27-28, 2011

Howard K. Gruenspecht[1]
U.S. Department of Energy

Assessment and valuation of the impacts of climate change on energy systems, including both effects on energy demand and effects on energy supply systems, have received considerable attention over the past 25 years. While the literature encompasses a wide range of results, recent assessments, including high-profile reports such as the Stern Review and the IPCC 4th Assessment Report that have identified a high likelihood of significant adverse impacts in other areas, have generally found modest impacts, both positive and negative, on energy systems. There is nothing in the more recent literature that suggests any major change in that assessment. Below, we review impacts on energy use for space heating and cooling which have been considered in most analyses of energy demand impacts, as well as other potential effects on energy demand. We also consider effects on energy supply systems, both new and existing. We conclude with summary observations about the analysis of energy impacts to date and identify factors that may be important in extending the literature.

Impacts on Space Conditioning Energy Demand: The most direct way in which climate change potentially affects energy demand is through its effect on energy use for heating and cooling. Some early studies of impacts on energy demand in the United States focused exclusively on the demand for electricity for cooling in the summertime. Subsequently, several papers noted that from the space conditioning perspective, the United States is a cold country, with expenditures on winter heating fuel several times higher than expenditures on electricity for cooling, and that some degree of warming would likely decrease overall demand and expenditures for space conditioning energy. The traditional grouping of "industrialized countries" -- the OECD countries plus Russia and Eastern Europe have an even larger gap between their baseline energy use and expenditures for heating and cooling, so initial warming is likely to provide savings in energy use and expenditures for space conditioning in

[1] The views expressed in this note, which draw on the author's past involvement with the literature on neregy impacts of climate change, go beyond topics that fall within the purview of the Energy Information Administration, where he now serves as Deputy Administrator. They should not be construed as reflecting the views of that agency.

those regions as well. The developing countries, which include both tropical and non-tropical areas, present something of a mixed bag, in part because the use of cooling equipment is highly sensitive to economic development as well as local climate conditions.

Any analysis of the impact of climate change on space conditioning energy use is likely to be highly sensitive to both the magnitude of climate change considered, and its detailed composition. The latitudinal, diurnal, and seasonal gradient of warming and changes in relative humidity all play a crucial role in determining whether warming reduces or increases energy use and/or expenditures for space conditioning at any particular location, or cumulatively across any set of locations. In part, the spread of results across studies on space conditioning impacts reflects different approaches to specifying the global warming scenarios that are considered.

Energy expenditure changes and measures of individual or aggregate comfort in buildings, a welfare indicator, may diverge considerably. On the one hand, the change in capital and energy expenditures for space cooling in a higher temperature and humidity scenario is likely to overstate the cost of maintaining a constant indoor summertime comfort level for those who acquire new space conditioning equipment in the face of climate change. Space cooling, unlike space heating, is subject to very significant threshold effects, even in relatively rich countries. [2] Once installed, cooling equipment is likely to be used to provide improved comfort relative to that which householders might have accepted under baseline conditions before the threshold was crossed. However, energy expenditure changes do not reflect the value of incremental indoor discomfort for those who do not cross the cooling equipment threshold. In addition, incremental summertime outdoor discomfort for the wider public, are not reflected at all in changes in space conditioning costs.

Energy implications of changes in space conditioning energy demand, which are of great interest to energy planners without regard to their value as welfare indicators, must be assessed in the context of technology changes over relevant time horizons. Assessments of energy impacts of climate change that are made without consideration of changes in energy technologies and practices can badly miss their mark. For example, the efficiency of new air conditioning units has nearly doubled since 1990, when the first studies claiming large impacts on summer peak energy load due to warming were published. More recently, the prospect of the smart grid and attendant opportunities to manage load in real time are likely to greatly ameliorate the implications of higher peak space conditioning loads for the electricity supply infrastructure, since other loads can now be more readily incentivized to "make room" for cooling loads.

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[2] For example, many homes along the California coast, and in Europe, both relatively wealthy regions of the world, do not have air conditioners. It is possible that climate change could result in the crossing of a comfort threshold that leads households to install such equipment.

__Other Energy Demand Impacts__: **While space conditioning impacts have been the focus of research on energy demand impacts, some other areas, including the energy-water nexus, merit additional attention.** Significant amounts of energy are used to supply water for household, agricultural, and industrial purposes, and also to move and treat wastewater from all categories of water use. The potential impact of climate change on water supply has been considered elsewhere in this workshop. To the extent that climate change has adverse impacts on water supply, the need to provide replacement water may have significant energy implications. Many types of replacement supplies, such as desalinization plants, long-distance pumping solutions, and cleaning of wastewater to a standard that allows for reuse, can use significantly higher amounts of energy than is required to supply water under baseline conditions. The issue can be important in both developed and developing country contexts.

__Energy Supply Systems: Access to Traditional Energy Resources.__ It is well known that climate change can have significant impacts on access to traditional energy resources. For example, hydroelectricity, by far the most significant source of renewable electricity in both the United States and the world today, is quite sensitive to patterns of precipitation and snowpack accumulation, which are in turn likely to be affected by climate change. The pattern of impacts is likely to vary across locations, and also to be dependent on both the passage of time and the extent of climate change. A traditional energy resource where the initial impact on supply is likely to be positive is the Arctic oil resource, as access would be significantly improved by a reduction in Arctic ice cover. However, not all northern latitude resources will necessarily benefit from climate change, as any change in permafrost conditions and the length of that annual hard freeze period could limit the ability to build and maintain energy infrastructures needed to access certain energy resources, both onshore and offshore, at high latitudes.

__Energy Supply Systems: Impacts on Existing Energy Supply Infrastructure__. Another category of energy supply impacts that has been extensively examined involves existing energy supply infrastructures that may be affected by changes in temperature or precipitation patterns. In addition to hydroelectric dams that are directly dependent on water flows, nearly all existing generating facilities require access to cooling water. As discussed above, climate change impacts are likely to include changes in precipitation, snowpack and evaporation patterns that will affect water availability and temperature in and around existing power plants. A change in cooling water availability and temperature can affect power plant operation. Changes in ambient air temperature can also affect the effective maximum capacity of existing units. However, it is questionable whether or not any of these impacts are quantitatively important in the overall context of climate change impacts after consideration of actions to mitigate and/or adapt to them.

Energy Supply Systems: Impacts on Non-Traditional Energy Sources. Given that energy-related emissions from the combustion of fossil fuels account for at least three-fifths of anthropogenic greenhouse gas emissions globally, and more than four-fifths of U.S. emissions, strategies to mitigate emissions often focus on the replacement of fossil fuels with emissions-free energy sources. Expanded use of wind, solar, and biomass energy for electricity generation, and the use of biofuels in the transportation sector, are often cited as potential alternatives to fossil fuels. Given this, it is important to consider the possible impacts of climate change on these technologies.

With respect to solar, both photovoltaic (PV) and solar thermal technologies are sensitive to changes in cloud cover. Pan et al. (2004) modeled changes in global solar radiation reaching the surface through the 2040s based on the Hadley Center Circulation model and projected a solar resource reduced by as much as 20 percent seasonally in key U.S. regions for solar energy, presumably from increased cloud cover. The energy assessment published by the U.S. Climate Change Science Program in February 2008 notes that aerosols can also play a role in cloud cover, and that interactions between aerosols and greenhouse gases are complex.

Biomass already rivals hydropower as a renewable energy source in the United States, and mandates for renewable fuel use in transportation first enacted in 2005 and then significantly strengthened in the Energy Independence and Security Act of 2007 call for biofuels to significantly grow in both absolute terms and as a share of the total liquid fuels used in transportation. Biomass also has growth potential in the electric power sector, where it can be co-fired with coal in existing power plants. Much attention in the recent literature and the regulatory sphere has focused on the carbon cycle impacts of increased biomass energy use, which depends on the sustainability of biomass cultivation and proper accounting practices. The impacts of climate change on the economics of biomass energy are closely related to the effects of climate change on agriculture, which are addressed in another part of this workshop.

Finally, with respect to wind, there is little information regarding the effects of climate change. The siting of wind farms and the cost of wind generation are both very sensitive to the specific location of the wind resource. One question that arises, in addition to the impact of climate change on overall available wind resource, is if climate change will cause shifts in wind patterns within the 20- to 30-year lifetime of wind projects.

Concluding Observations:

1. Energy is a sector that is likely to be impacted by climate change. As climate changes considered grow ever larger, common sense suggests that negative impacts on energy use and supply will dominate, but for small to modest climate change it is quite possible that net energy ”damages” will be negative.

2. For energy, as in some other sectors where impacts must be assessed, the devil is really in the details, such as, but not limited to, the assumed latitudinal, seasonal, and diurnal gradient of climate change, and its effects on humidity, cloud cover, and wind patterns as well as its effect on temperature. Studies that make different assumptions in these areas can reach wildly different conclusions even if they are both carefully executed.
3. Future impacts of climate change on energy systems will occur in the context of future opportunities for adaptation and responses. While it is hard to predict the future, it is important to consider the implications of the past track record of technology improvements and the impact of technologies now being deployed in assessing the cost of adaptation and response strategies.
4. It is useful to distinguish between energy system impacts, which are of greatest importance to energy planners, and energy-system-related welfare impacts, which are of primary importance to cost-benefit analysis of policies to address climate change.
5. Both analysts and research funders can advance the utility and credibility of research on energy system impacts of climate change through a commitment to carefully scope and prioritize research needs in the area.

Energy System Impacts of Climate Change: Background Slides

for

EPA/DOE Workshop on Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis

Washington DC
January 27-28, 2011

Howard Gruenspecht, Deputy Administrator

U.S. Energy Information Administration
Independent Statistics and Analysis

Despite a continued shift of the U.S. population to warmer areas, much more energy is used to heat buildings than to cool them through 2035

Projected Space Conditioning Energy Use in Buildings, Quadrillion Btu

Residential	2010	2015	2025	2035
Space Heating	**4.33**	**4.27**	**4.18**	**4.10**
Purchased Electricity	0.29	0.28	0.30	0.31
Natural Gas	3.29	3.27	3.28	3.27
Distillate Fuel Oil	0.50	0.48	0.39	0.33
Liquefied Petroleum Gases	0.26	0.23	0.21	0.19
Space Cooling	**1.11**	**0.82**	**0.90**	**0.99**
Purchased Electricity	1.11	0.82	0.90	0.99
Natural Gas	0.00	0.00	0.00	0.00
Ventilation	0.14	0.15	0.18	0.19
Commercial				
Space Heating	**1.93**	**2.01**	**2.04**	**2.04**
Purchased Electricity	0.18	0.17	0.17	0.18
Natural Gas	1.61	1.70	1.75	1.76
Distillate Fuel Oil	0.14	0.13	0.11	0.10
Space Cooling	**0.62**	**0.56**	**0.60**	**0.65**
Purchased Electricity	0.58	0.53	0.56	0.61
Natural Gas	0.04	0.04	0.04	0.04
Ventilation	0.51	0.55	0.64	0.71

Source: EIA AEO2011 Reference case

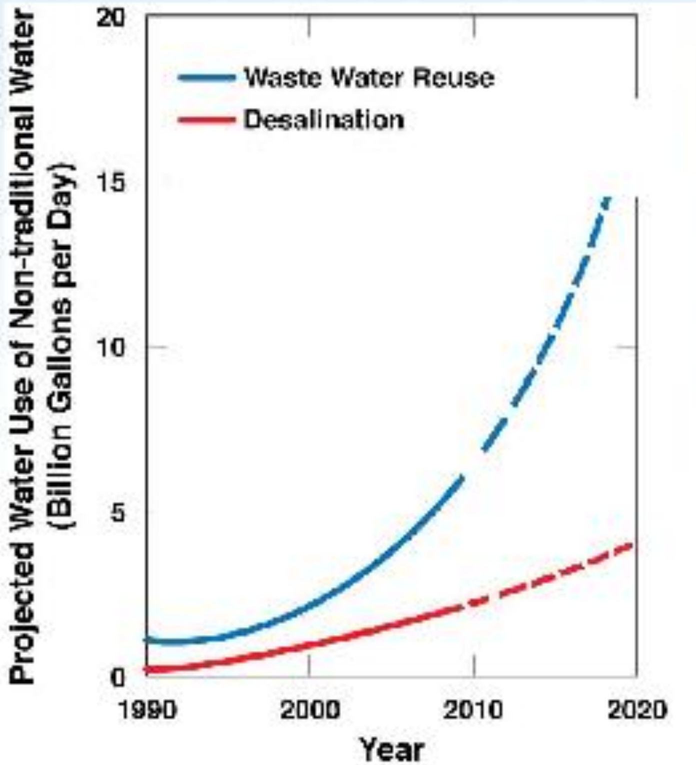
Despite a continued shift of the U.S. population away from cold areas, projected energy expenditures to heat buildings exceed cooling expenditures by a wide margin through 2035

Space Conditioning Energy Expenditures in Buildings, Billions of Year 2009 Dollars

Residential	2010	2015	2025	2035
Space Heating	**63.47**	**59.90**	**65.74**	**69.86**
Purchased Electricity	9.66	9.09	9.43	9.83
Natural Gas	36.65	33.74	39.08	44.21
Distillate Fuel Oil	10.33	10.14	10.12	9.03
Liquefied Petroleum Gases	6.82	6.93	7.11	6.80
Space Cooling	**37.42**	**26.31**	**28.09**	**31.46**
Purchased Electricity	37.42	26.31	28.09	31.46
Natural Gas	0.00	0.00	0.00	0.00
Ventilation	4.66	4.93	5.65	6.17
Commercial				
Space Heating	**22.12**	**21.75**	**24.56**	**26.94**
Purchased Electricity	5.00	4.58	4.59	4.82
Natural Gas	14.59	14.64	17.26	19.52
Distillate Fuel Oil	2.53	2.54	2.70	2.60
Space Cooling	**16.94**	**14.51**	**15.37**	**16.97**
Purchased Electricity	16.54	14.20	15.02	16.58
Natural Gas	0.40	0.31	0.35	0.39
Ventilation	14.55	14.95	17.05	19.30

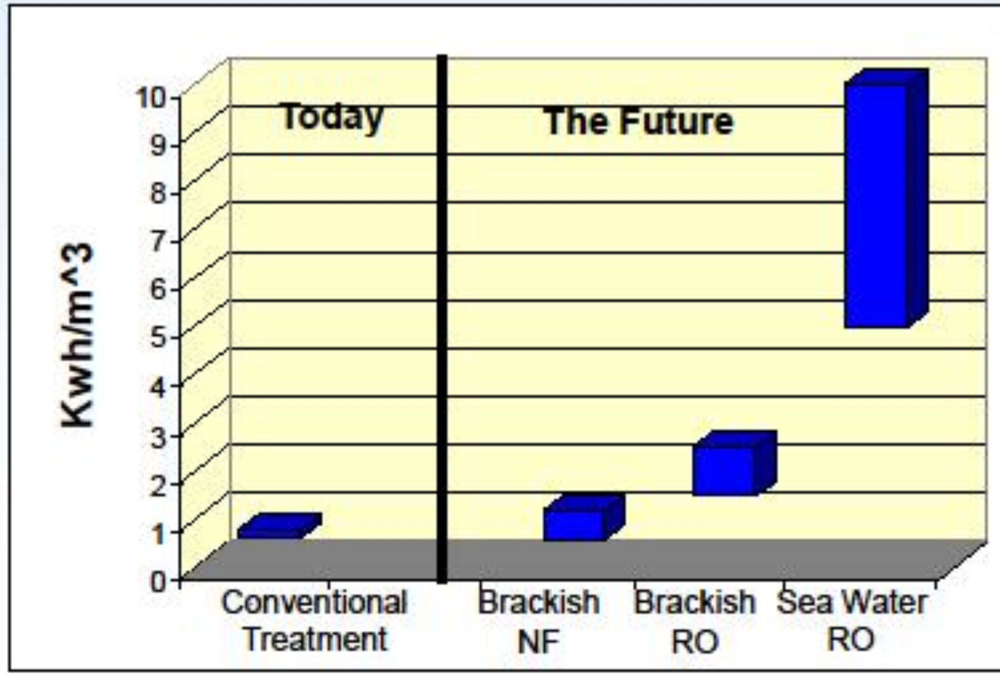
Source: EIA AEO2011 Reference case

Growing Use of Non-traditional Water Resources



(Modified from Water Reuse 2007, EPA 2004, Mickley 2003)

Power Requirements For Treating



(Einfeld 2007)

- Desal growing at 10% per year, waste water reuse at 15% per year
- Reuse not accounted for in USGS assessments
- Non-traditional water use is energy intensive

Source: Mike Hightower, Sandia National Laboratory

For more information

U.S. Energy Information Administration home page	www.eia.gov
Short-Term Energy Outlook	www.eia.gov/emeu/steo/pub/contents.html
Annual Energy Outlook	www.eia.gov/oiaf/aeo/index.html
International Energy Outlook	www.eia.gov/oiaf/ieo/index.html
Monthly Energy Review	www.eia.gov/emeu/mer/contents.html
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Impacts of Climate Change on Global Electricity Production and Consumption: Recent Literature and a Useful Case Study from California

Jayant Sathaye
Lawrence Berkeley National Laboratory, Berkeley

Abstract

Climate change affects both energy demand and energy supply through various parameters. These parameters include warmer air and water caused by higher temperatures, changes in flow of rivers, snowfall and ice accretion, coastal inundation, wildfires, soil conditions, cloudiness and wind speeds. Increases in energy demand and supply loss create a combined problem for ensuring an adequate supply of fuels and electricity. Projections of these parameters combined with those of energy demand and supply over the next century are needed to improve our understanding of the increased vulnerability of the energy sector. In addition, a detailed physical layout of the various facilities is necessary to understand the exposure of energy infrastructure to the climate-related challenges. Despite a potentially significant impact on energy demand and supply, the international literature base on these topics is very limited particularly in the developing countries and on the supply component. As a result, this presentation reports on selected international quantitative evaluations of energy demand, qualitative evaluations of energy supply impacts, and related policy implications. Given the limited amount of literature on this subject, we discuss an approach that we have used for evaluating the impact of climate change on the California energy demand and supply systems. We believe this method could provide insights and form the basis for "bottom-up" evaluations in other countries.

Table 1 shows the hydro-meteorological and climate parameters for selected energy uses. This table indicates the various connections between the sets of parameters. For example, changes in air temperature would affect electricity generation efficiency including that of solar PV panels and the demand for cooling and heating. Robust evaluation of energy supply and demand impacts should examine each of the listed parameters while also taking into consideration the interconnections between them. Warmer temperatures may affect generation, transmission and transformer substations leading to a compounded impact.

A number of papers discuss how cooling and heating energy use will be affected by projected changes in temperature. Previous analyses of climate impacts on demand has shown that the overall impact of higher temperatures is likely to reduce demand for heating more than the effect of increased cooling load.

Adjusting for other variables such as income and energy price is also important in assessing the effect of temperature increases. A recent publication (Petrick et al. 2010)[1] evaluates residential data for 157

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[1] Petrick S., K. Rehdanz, and R. Tol (2010). *The impact of temperature changes on residential energy consumption.* Kiel Institute for the World Economy, No. 1618.

countries over three decades and shows that energy use declines due to rising temperatures indicating that reduction in heating has played a more important role than the increase in air conditioning load.

An analysis using the POLES Model for Europe (EU27) also notes that only a limited literature develops the discussion of these issues, and no definitive conclusions exist about quantified evaluations of these impacts and their respective costs (Mima et al. 2010)[2]. Mina et al. (2010) This paper estimate that European energy expenditures on supply-side resources will be $65 billion higher in 2100 – or0.08 percent of GDP – in one climate change scenario. Conversely, energy expenditures on the demand side are projected to decrease by $480 billion for heating and increase by $10 billion for cooling. Another paper by Isaac and Van Vuuren (2009)[3] estimates that global heating energy demand decreases by 800-1000 Mtoe while cooling demand increases by 80-100 Mtoe by 2100.

Table 1: Hydro-meteorological and Climate Parameters for Select Energy Uses

Hydro-meteorological and/or climate parameter	Select energy uses
Air temperature	Turbine production efficiency, air source generation potential and output, demand (cooling/heating), demand simulation/modeling, solar PV panel efficiency
Rainfall	Hydro-generation potential and efficiency, biomass production, demand, demand simulation/modeling
Wind speed and/or direction	Wind generation potential and efficiency, demand, demand simulation/modeling
Cloudiness	Solar generation potential, demand, demand simulation/modeling
Snowfall and ice accretion	Power line maintenance, demand, demand simulation/modeling
Humidity	Demand, demand simulation/modeling
Short-wave radiation	Solar generation potential and output, output modeling, demand, demand simulation/modeling
River flow	Hydro-generation and potential, hydro-generation modeling (including dam control), power station cooling water demands
Coastal wave height and frequency, and statistics	Wave generation potential and output, generation modeling, off-shore infrastructure protection and design
Sub-surface soil temperatures	Ground source generation potential and output
Flood statistics	Raw material production and delivery, infrastructure protection and design, cooling water demands
Drought statistics	Hydro-generation output, demand
Storm statistics (includes strong winds, heavy rain, hail, lightning)	Infrastructure protection and design, demand surges
Sea level	Offshore operations, coastal energy infrastructure

Formal analysis of impacts of climate change on energy supply infrastructure is extremely limited. Studies exist for the UK, Brazil, and the US state of Alaska, but there may be other studies currently being conducted elsewhere. Lawrence Berkeley National Laboratory (LBNL) is in the process of completing a "bottom-up" study for California. The results of which are described below. This multi-year research effort included participation by utility companies in a technical advisory role.

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[2] Mima S. and Criqui P. (2010). *Analysis of Europe energy system in the POLES model A1B case under future climate change. Draft Report*, LEPII, Grenoble.

[3] Isaac M. and D. Van Vuuren (2009). Modeling global residential sector energy use for heating and air conditioning in the context of climate change. *Energy Policy*

Our study examined the impact of climate change on California energy infrastructure, including the San Francisco bay region. We estimated second-order impacts on power plant generation, transmission line and substation capacity during heat spells, wildfires near transmission line corridors and a limited study of sea level encroachment on power plants, substations and natural gas facilities.

We conclude that negative impacts on electricity infrastructure can be avoided, if climate change is anticipated and sufficient adaptation measures are employed. These measures might include installing new generation, substation, and transmission capacity, improving energy efficiency, and increasing investments in cooling equipment and wildfire mitigation strategies.

More specifically, the study finds that higher temperatures will decrease the capacity of existing natural gas fired power plants to generate electricity during particularly hot periods in the future. The estimated decrease in capacity varies by region, emission scenario, climate model, and plant type. During the hottest periods in August (at the end of the century) and under the high emission scenario (A2), our models estimate a decrease in simple cycle natural gas power plants generating capacity of3%-6% in California and 3%-4% in the San Francisco region. Under similar conditions, our models suggest diminished transformer and substation capability—between 2 and 4% across California and between 2 and 3% in the San Francisco region with a small increase in transmission line carrying capacity.

Climate change and fire risk may pose a more difficult challenge to the electric utilities. Our work, building on the results of existing fire studies, suggests that higher temperatures resulting from climate change will increase fire risk to transmission lines in California, including the San Francisco region. For example, the likelihood of fires occurring next to large transmission lines is expected to increase dramatically in parts of California and San Francisco at the end of the century, under some climate scenarios. It should be noted that fires do not always cause electricity outages—they more often increase electricity maintenance costs and decrease transmission line efficiency. In addition, rising sea levels at the end of the century could flood as many as 25 power plants, scores of electricity substations and numerous natural gas facilities located along the coast of California and within the San Francisco region. Properly anticipated however, flooding could be avoided by building dykes, moving plants to higher elevations and other preventative actions. We also conducted site visits to several power plants and learned that the vertical resolution of California coastal topography is of a coarse resolution, which makes estimating impacts at the local level very difficult. We also learned that electricity infrastructure was occasionally not located at the latitude and longitude reported in the database that was supplied to us.

We concluded that electric utilities can deal with anticipated climate change, but we also recognize that the level of system capacity needed to do this may be difficult to quantify and finance. It is clear that utility engineering practices traditionally used to determine generation or transmission capacity may need to be revised. Similarly, utility tariff setting guidelines may need to be altered to finance the necessary infrastructure to maintain system reliability. In short, uncertainty about climate change is likely to pose both institutional and scientific challenges of a type that go beyond the scope of the current study. These institutional challenges may present as large a problem to the electricity system of California as the economic costs of anticipated climate change described in this study.

Impacts of Climate Change on Global Energy Production and Consumption:
Recent Literature and a Useful California Case Study

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DOE/EPA Climate Damages Workshop II
Washington D.C.

BERKELEY LAB

Presentation Outline

I. Context

II. Selected Review of International Impact Analyses

III. U.S. Case Study: California

IV. Lessons Learned

Presentation Context

- Traditional focus has been on GHG mitigation policy effects to this sector.
- General lack of impacts information for the energy sector, but base of international literature is growing.
- Qualitative "scoping studies", global, and regional risk assessments are underway.
- Analysis methods carried out in our ongoing research into California energy infrastructure at risk to climate change could be replicated in other regions, especially probabilistic and risk-based mapping.

Presentation Context:
Parameter Impacts on Energy Demand and Supply

Hydro-meteorological and/or climate parameter	Select energy uses
Air temperature	Turbine production efficiency, air source generation potential and output, demand (cooling/heating), demand simulation/modeling, solar PV panel efficiency
Rainfall	Hydro-generation potential and efficiency, biomass production, demand, demand simulation/modeling
Wind speed and/or direction	Wind generation potential and efficiency, demand, demand simulation/modeling
Cloudiness	Solar generation potential, demand, demand simulation/modeling
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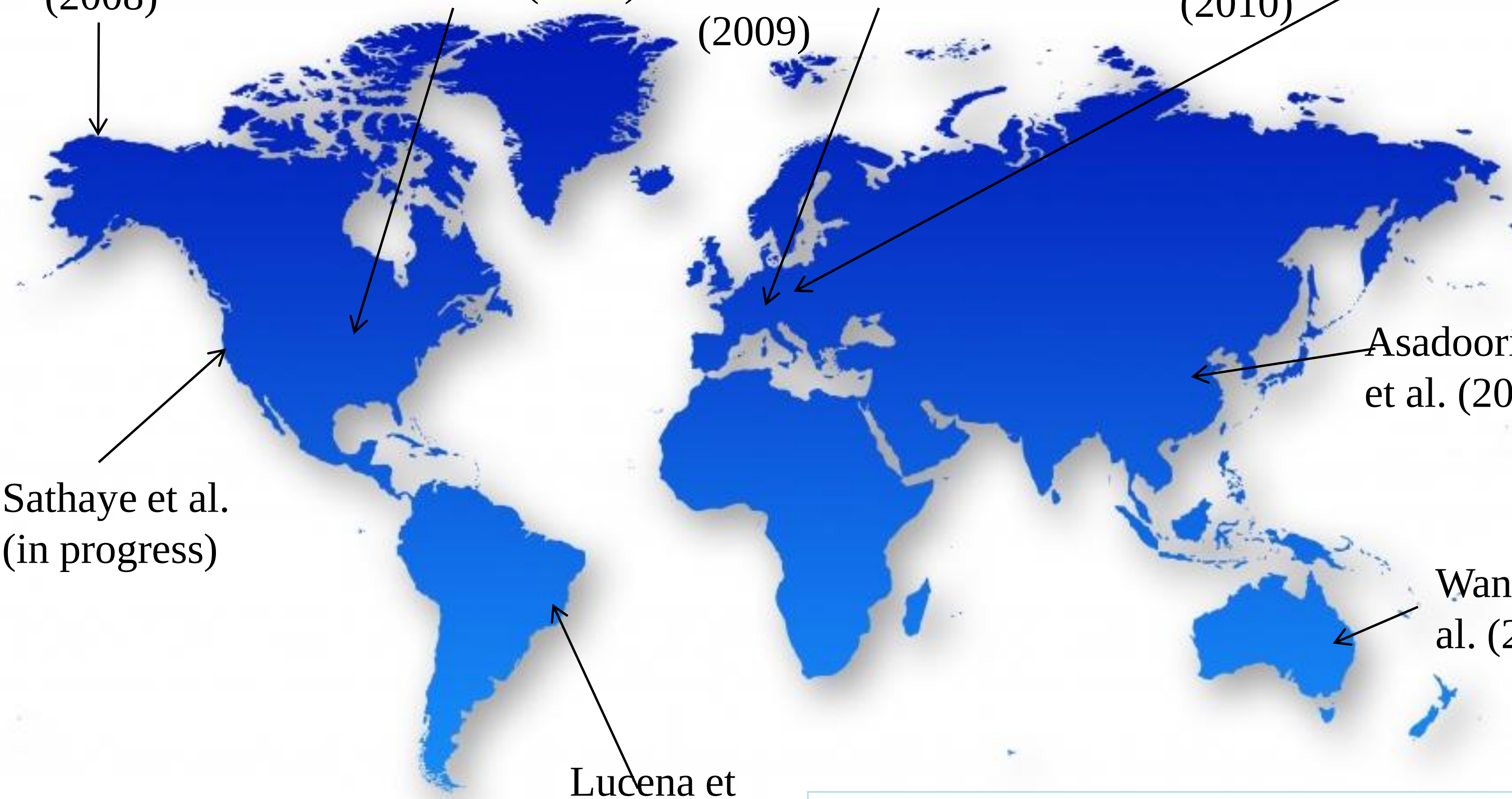
Selected Research List: Global, National and Local



GLOBAL:

- Vergara et al./World Bank (in progress)
- Petrick et al. (2010)
- Wilbanks et al./IPCC-AR4 (2007)

Selected Research: Global and Multi-national

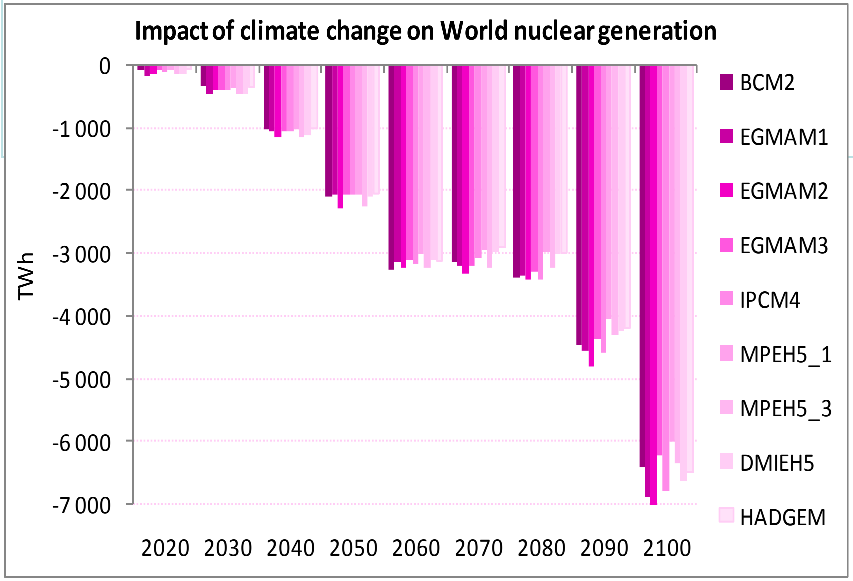
Climate impact on energy demand:

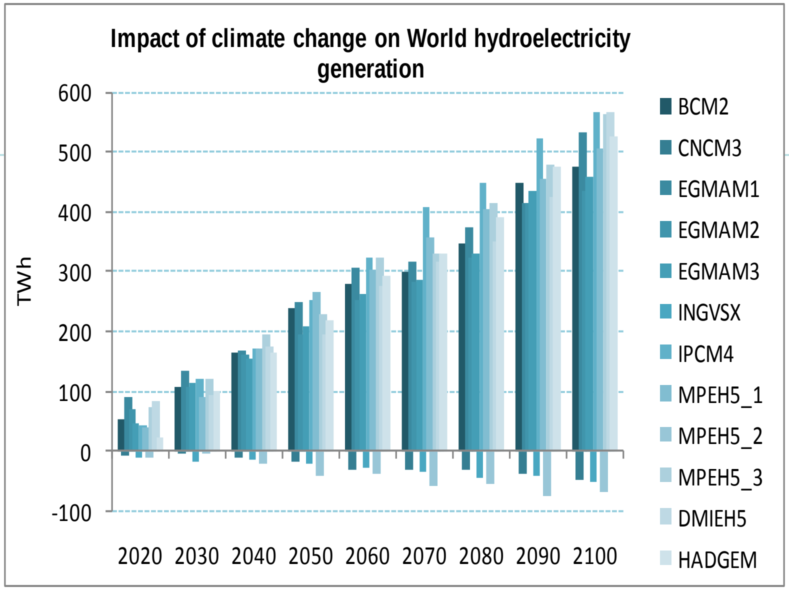
- **Heating Demand:**
  - Models typically show a <u>decline in heating demand </u>with rising temperatures
  - **e.g.,** Mina et al.(2010) using the A1B reference scenario in the POLES model show a decline that ranges from 200-300 Mtoe (-38% to -62%) by 2100.
- **Cooling Demand:**
  - Models show an <u>increase in cooling demand</u> with rising temperatures
  - **e.g.,** Increase in cooling demand is typically lower than the increase in heating demand – 60-130 Mtoe in the POLES model

Selected Research: Global and Multi-national

Climate impact on energy supply:

- Quantitative analysis of global supply options is limited to date
- **e.g.,** POLES model shows that hydroelectricity generation may increase or decrease depending on the scenario, while nuclear and thermal generation declines by 2100





Selected Research: National

~Least-cost adaptation options for the Brazilian electric power system (Lucena et al. 2010)~

- Researchers applied an integrated resource planning approach to calculate least-cost adaptation measures to a set of projected climate impacts in 2100 on the Brazilian power sector.
    - Used MAED (demand) and MESSAGE (supply) models, and A2 and B2 scenarios
- Focus is on impacts on electricity demand, hydropower capacity factor, and natural gas efficiency
    - Electricity demand increases in residential and service sectors by 6% and 5%
    - Hydropower firm capacity factor declines by about 30%
    - Natural gas generation decreases by about 2%
- Above impacts are offset by efficient adaptation technologies, and increased use of renewable, nuclear and thermal plant use

Selected Research: Local/Regional

~Alaska Infrastructure at Risk (Larsen et al. 2008)~

- Developed preliminary model to estimate quantitative risk to AK public infrastructure, including energy systems. Model estimated additional costs with and without adaptation scenarios and included probabilistic framework. Researchers acknowledged shortcomings including the need to: 1) improve count/value of infrastructure, 2) develop "ground-truthed" damage functions, and 3) properly discount uncertain future risk to the present.

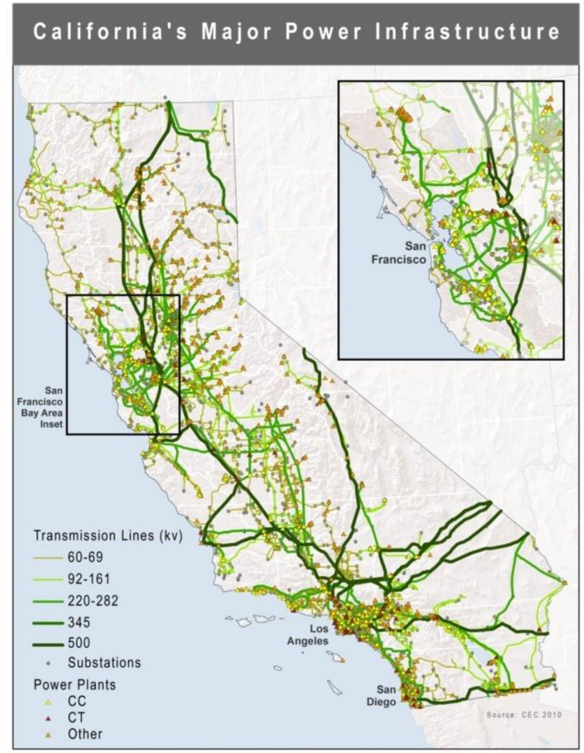
~California Energy Infrastructure at Risk (Sathaye et al.; in progress)~

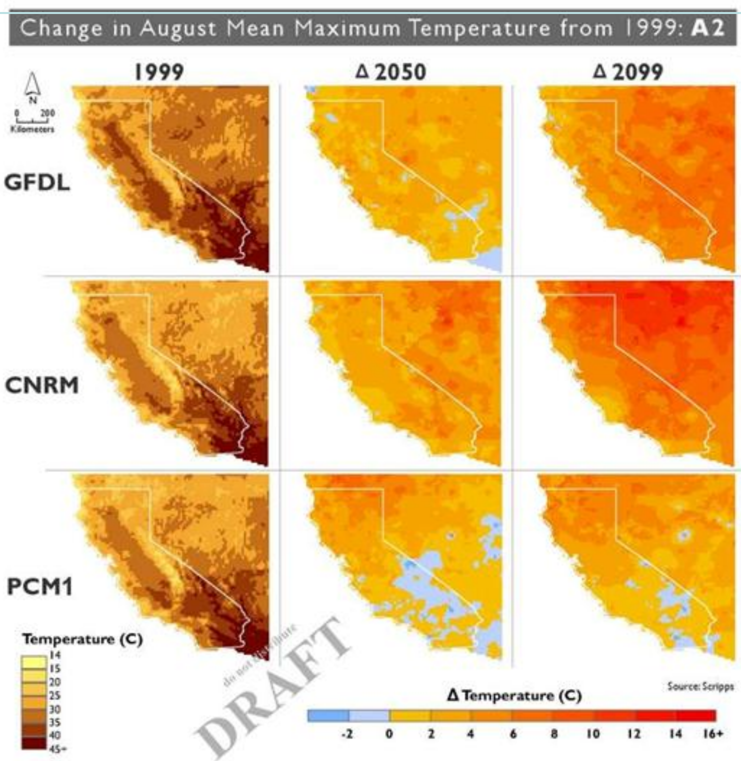
- Estimating risk to power plant, substation, and transmission line performance to projected temperature maximums. Team is overlaying reported energy infrastructure locations on top of sea-level rise and wildfire projections and visiting sites to ground-truth modeled results.

Case Study: Risk to CA Energy Infrastructure

BACKGROUND:

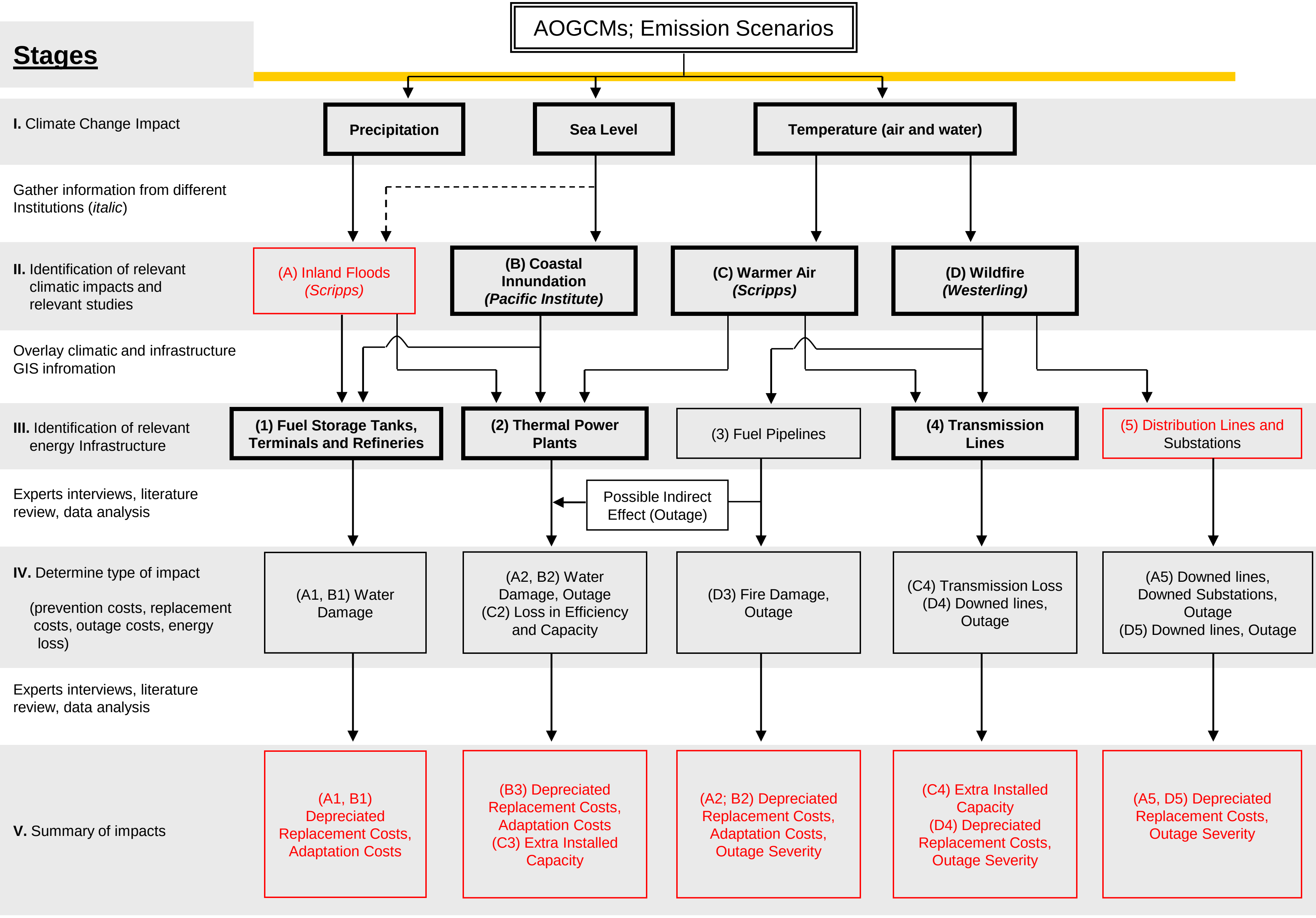
- California Energy Commission funded study to estimate power demand and explore physical risk to CA energy supply system.
- Technical advisory committee, including power sector stakeholders, provide feedback on data sources and methods.
- Estimated risk for A2 and B1 scenarios for three time periods up to 2100





BASIC METHOD:

- Coupled downscaled AOGCM projections to electrical system thermal equations to estimate changes to system capacity and demand from increased ambient temperature.
- Overlaid sea-level rise estimates and wildfire projections with known location of CA energy infrastructure.


AOGCMs; Emission Scenarios
Stages
I. Climate Change Impact
Precipitation
Sea Level
Temperature (air and water)
Gather information from different Institutions (italic)
II. Identification of relevant climatic impacts and relevant studies
(A) Inland Floods (Scripps)
(B) Coastal Innundation (Pacific Institute)
(C) Warmer Air (Scripps)
(D) Wildfire (Westerling)
Overlay climatic and infrastructure GIS infromation
III. Identification of relevant energy Infrastructure
(1) Fuel Storage Tanks, Terminals and Refineries
(2) Thermal Power Plants
(3) Fuel Pipelines
(4) Transmission Lines
(5) Distribution Lines and Substations
Experts interviews, literature review, data analysis
Possible Indirect Effect (Outage)
IV. Determine type of impact
(prevention costs, replacement costs, outage costs, energy loss)
(A1, B1) Water Damage
(A2, B2) Water Damage, Outage (C2) Loss in Efficiency and Capacity
(D3) Fire Damage, Outage
(C4) Transmission Loss (D4) Downed lines, Outage
(A5) Downed lines, Downed Substations, Outage (D5) Downed lines, Outage
Experts interviews, literature review, data analysis
V. Summary of impacts
(A1, B1) Depreciated Replacement Costs, Adaptation Costs
(B3) Depreciated Replacement Costs, Adaptation Costs (C3) Extra Installed Capacity
(A2; B2) Depreciated Replacement Costs, Adaptation Costs, Outage Severity
(C4) Extra Installed Capacity (D4) Depreciated Replacement Costs, Outage Severity
(A5, D5) Depreciated Replacement Costs, Outage Severity

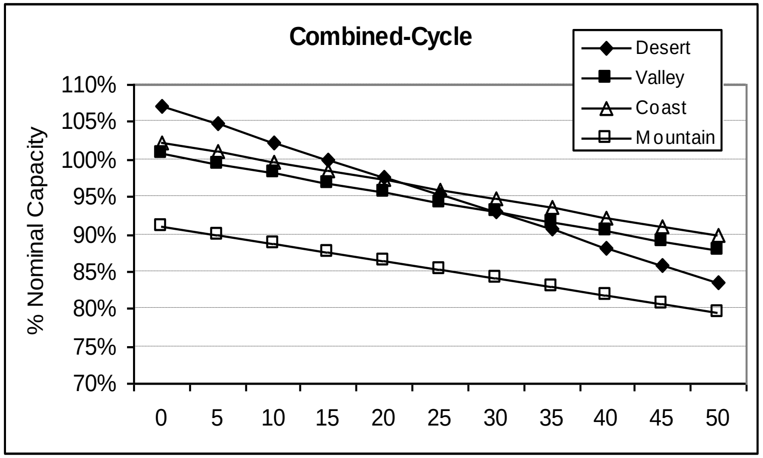
Overview of Research: Assessing vulnerability of….

1. *Electricity infrastructure* to **warming temperatures**.

- Literature review to determine quantitative relationships between ambient temperature and power plant, substation, and transmission capacity.

- Estimated potential physical impacts without adaptation/growth scenarios and reported results using mapping and numerical simulation software.

Without additional cooling equipment, CA natural gas-fired power plants typically lose ~0.7% to 1.0% of capacity for every degree of ambient temperature above 15C.

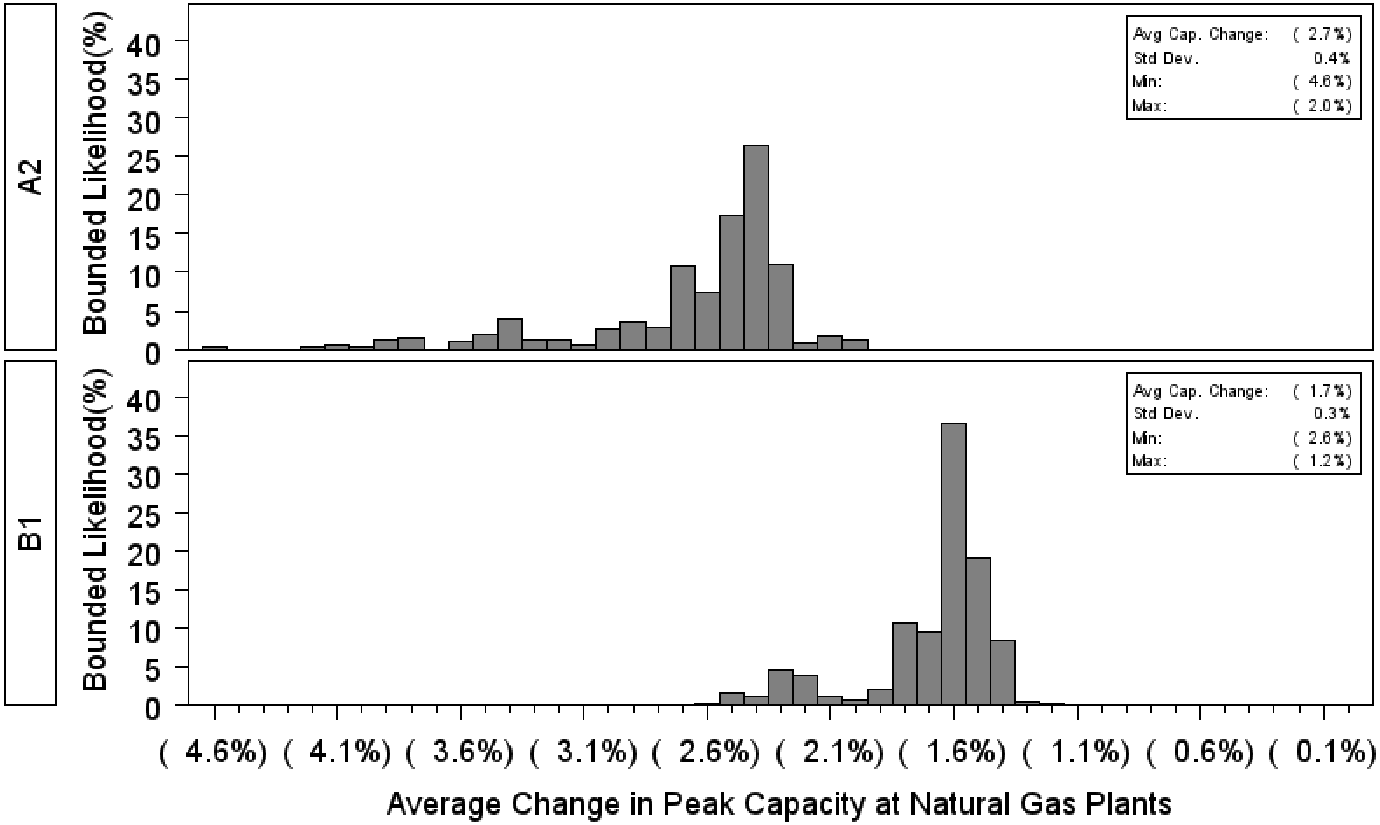


Temperature (Degrees Celsius)

Without additional cooling equipment, CA substations typically lose ~1.0% of capacity for every degree of ambient temperature above 30C.

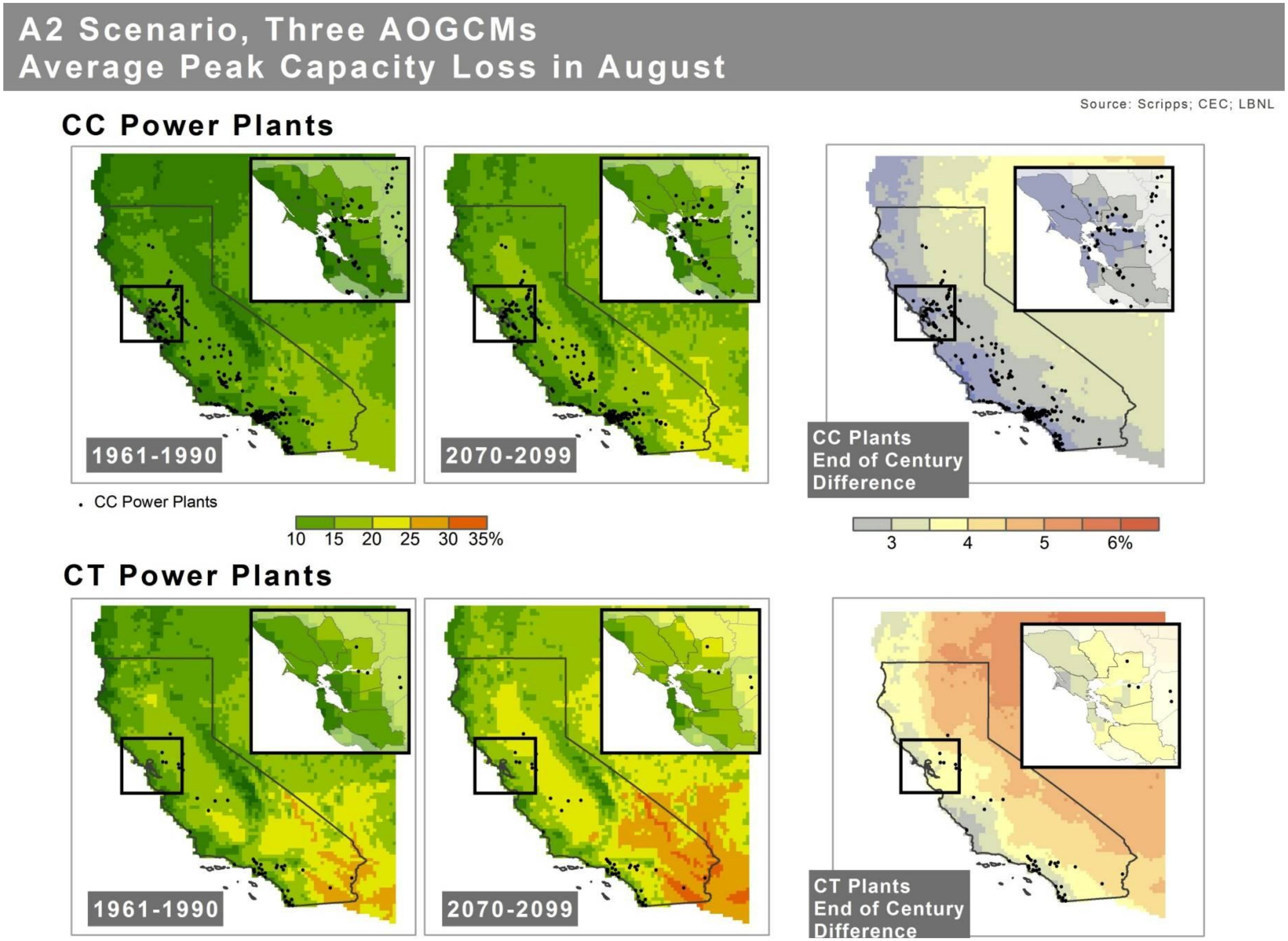
End-of-Century Incremental Impact Distributions

Natural gas-fired Power Plants



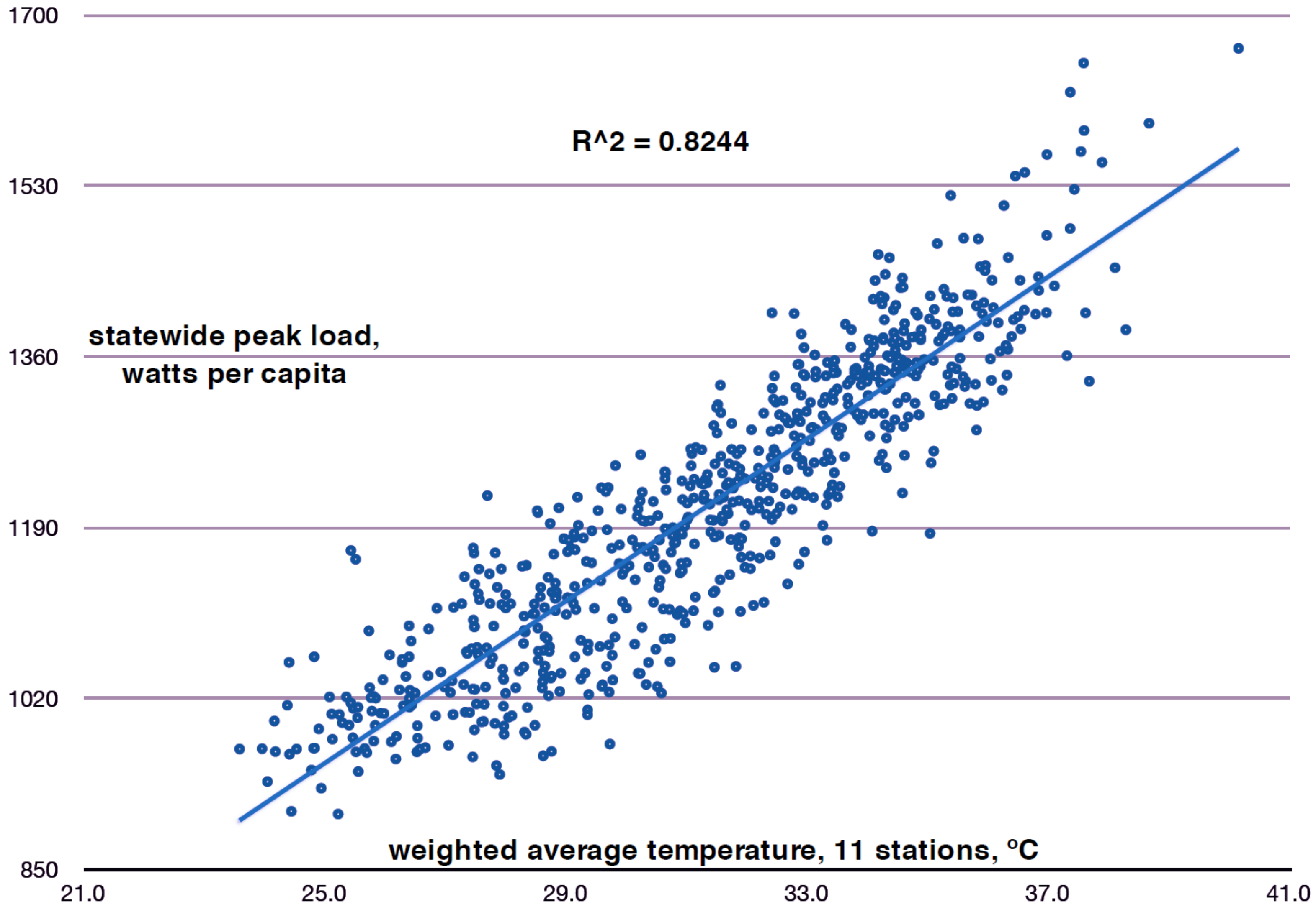
- *Warming temperatures may lead to* ***loss up to 4,000 megawatts (4%)*** *of available natural gas-fired power plant capacity.*
- *Incremental* losses are reported (i.e., losses above and beyond the losses estimated for the base period: 1961-1990).

End-of-Century Impact Mapping



Absolute Capacity Reductions — *Incremental Reduction*

Peak demand load vs. peak temperature



Electricity Demand and Supply: Results Summary

- **Peak Capacity Losses**

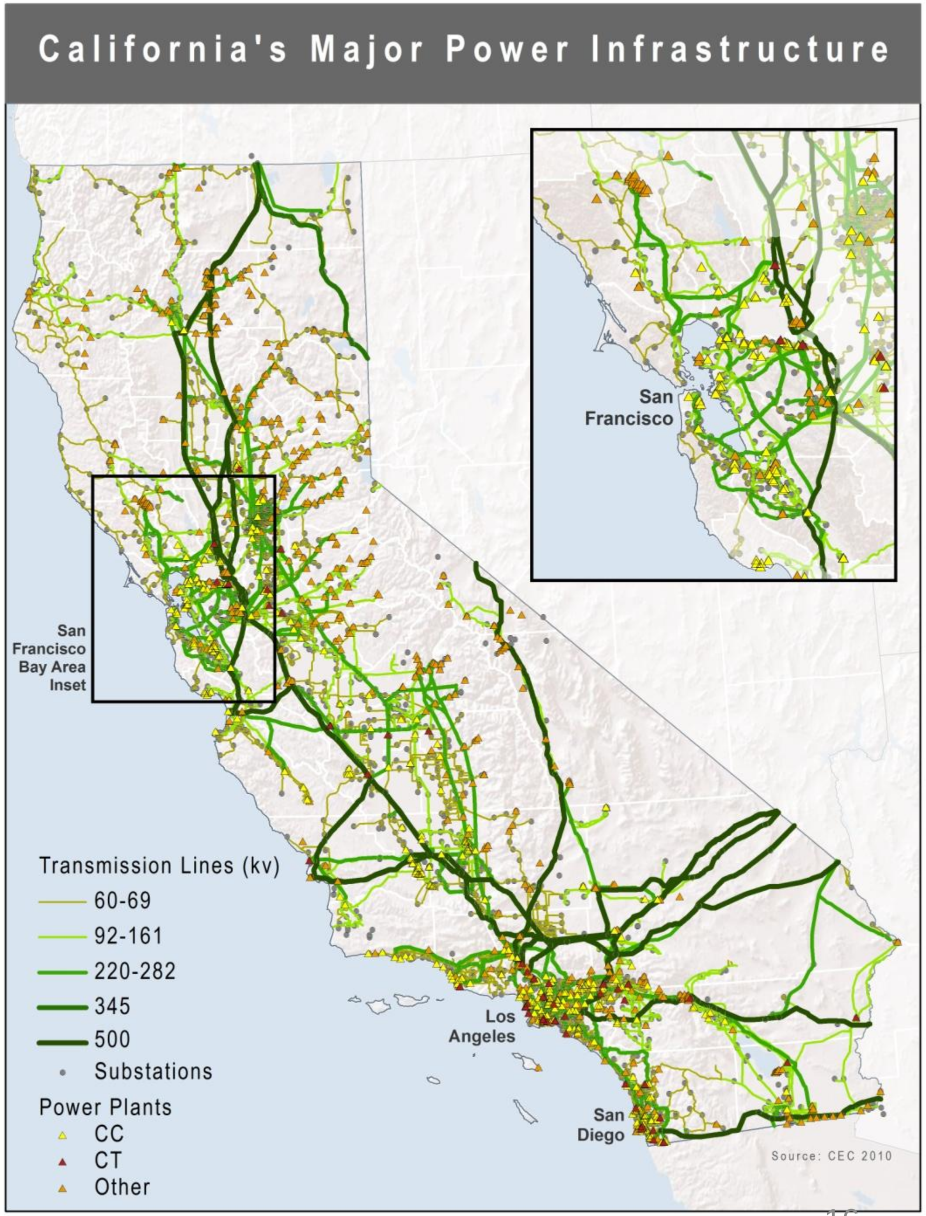
- Natural gas-fired power plants
  - up to 4000 MW (4%)

- Electricity supply sub-stations
  - 1.6% to 2.7%

- Transmission lines
  - Limited data on sizes, locations, and usage capacity
  - ~7%

- Cooling demand
  - 20% increase in peak load

- Demand and supply combined effect
  - 24%

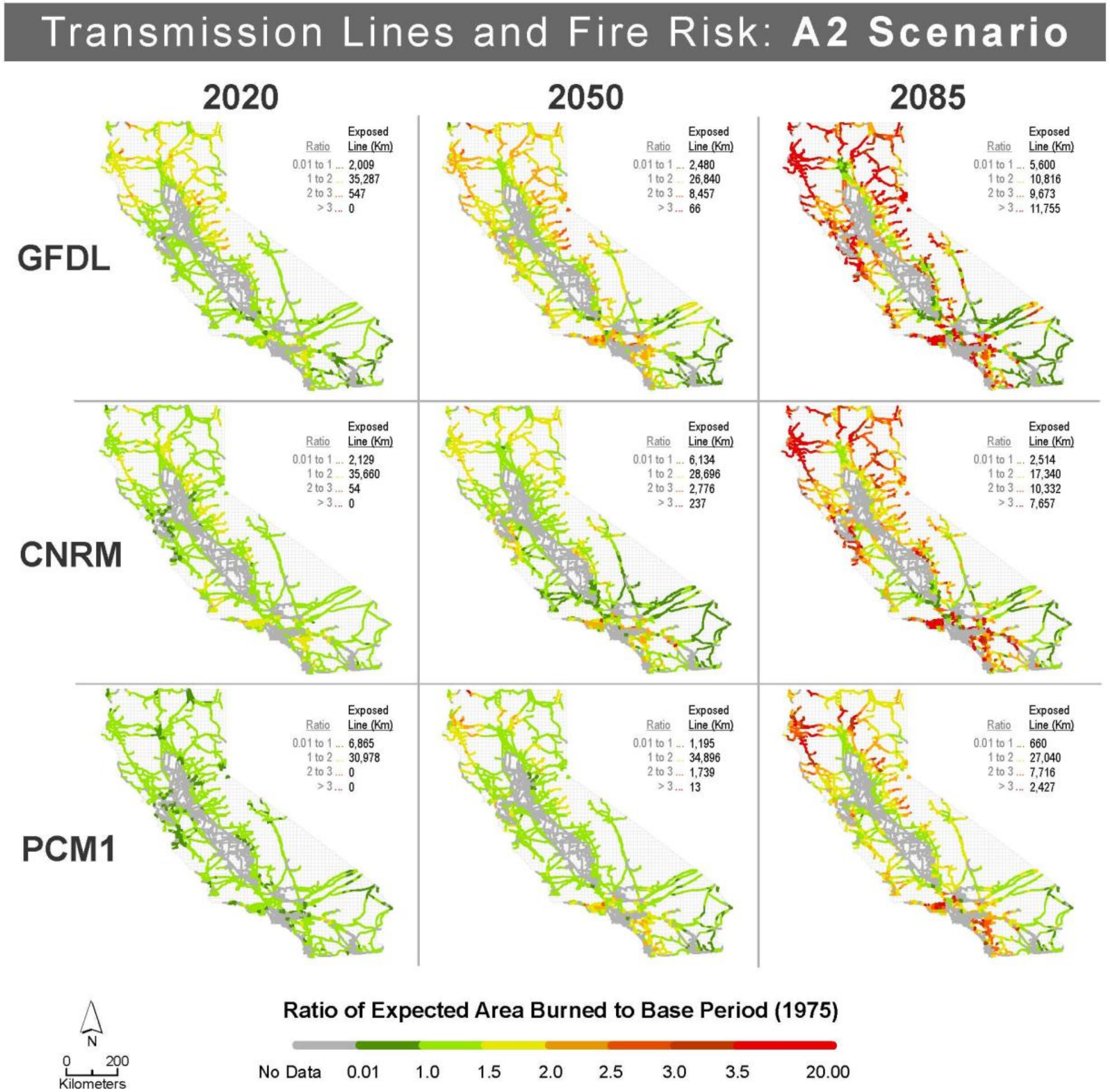


Overview of Research: Assessing vulnerability of….

2. *Electricity infrastructure* to **wildfires**.

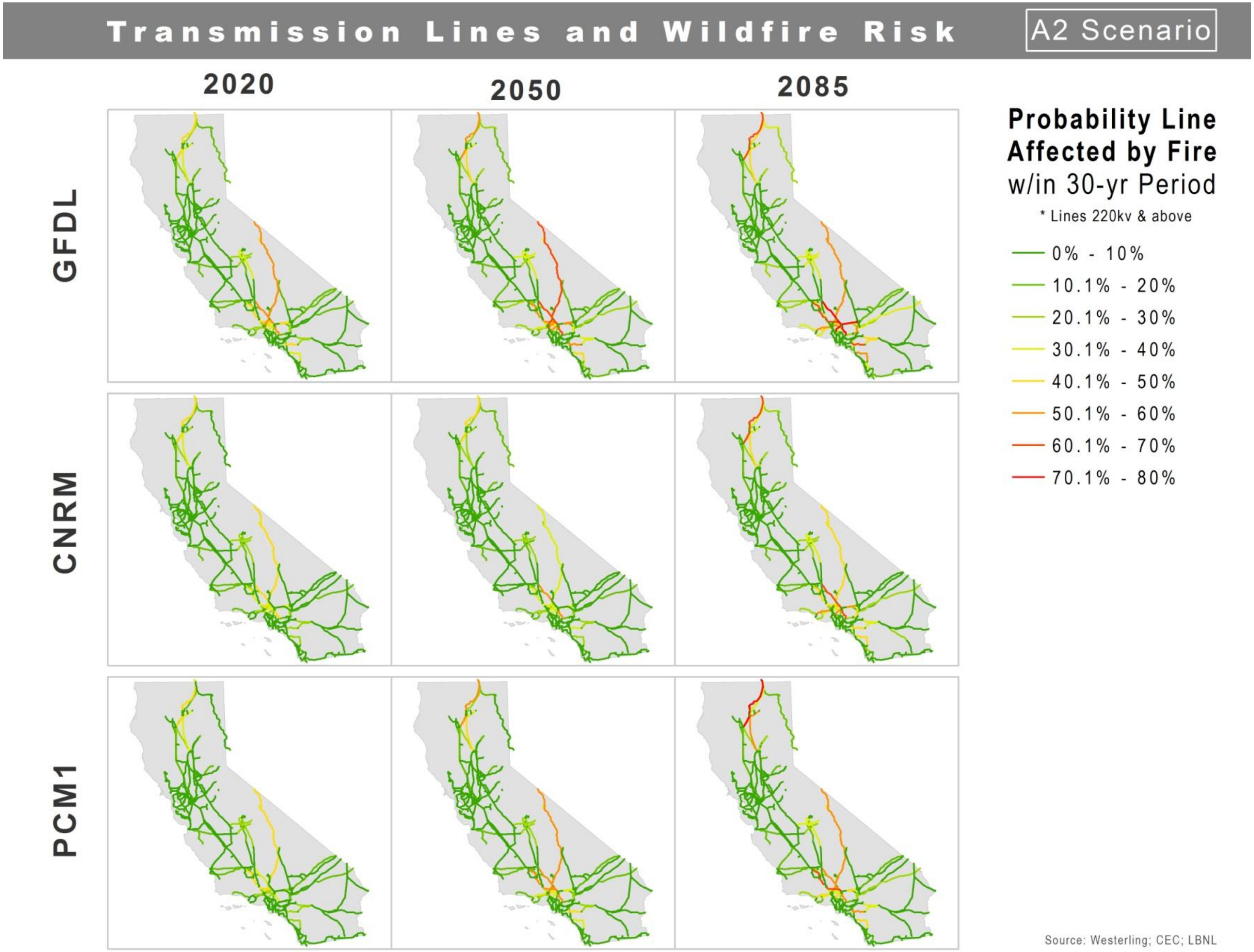
- *Discuss* **climate factors** affecting wildfires
- *Overlay* transmission lines on **near-term** spatial models of wildfire probability
- *Overlay* transmission lines on **long-term** spatial models of wildfire (as influenced by climate projections)
- *Quantify* transmission length of **lines exposed to wildfires** under modeled future climate scenarios

Length of Transmission Lines Potentially Impacted: Increase in burned area within cells ($1/8^0$)



- Coarse spatial resolution of fire projection data limited our impact analysis to the length of line in a fire-prone area.

Projected fire risk to transmission lines for the A2 scenario



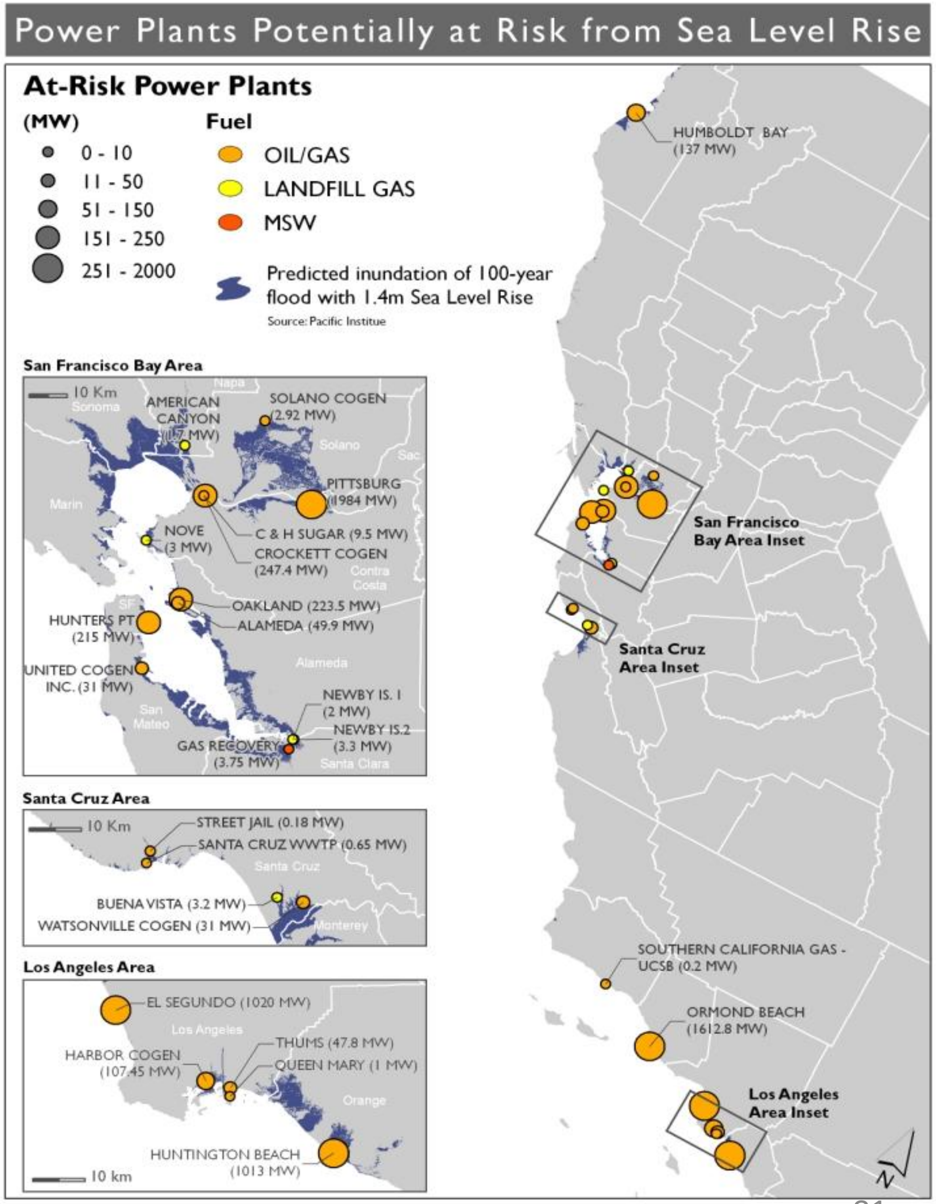
Overview of Research: Assessing vulnerability of….

3. *Electricity, natural gas, and other energy infrastructure* to **sea level rise**

- *Review* current sea level trends
- *Incorporate* data:
  - Land area affected by sea level rise (Pacific Institute, Knowles)
  - Power plant, substation, natural gas locations (CEC)
- *Mapping* analysis:
  - *Overlay* infrastructure locations over sea level areas
  - *Compare* LBNL and Pacific Institute study results

Sea Level Rise Impact Mapping & Comparisons

- Projected sea level rise – 1.4 meters
- 25 power plants and about 90 substations are vulnerable to sea level rise
- Humboldt Bay and Antioch Site visits indicated that coarse vertical resolution of CA topography may have over- or under-stated impacts in power plant locations.



Lessons Learned

- General lack of quantitatively-based impacts information for energy sector, but base of international literature is growing.
- Projected global heating demand reduction due to higher temperatures is larger than the increase in cooling demand
- Temperature impact on demand is much higher than on supply infrastructure
  - Impact on hydropower supply may increase or decrease generation depending on water supply conditions
- Impact of wildfires could potentially be significantly high
- More data and research are needed to evaluate wildfire and sea level rise impacts on the power sector infrastructure and temperature impacts on electricity transmission and distribution

Acknowledgements for CA Research

List of Authors:

- Jayant Sathaye, Larry Dale, Peter Larsen, and Gary Fitts (LBNL)
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Regional Conflict and Climate Change

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Paper prepared for the workshop on Research on Climate Change Impacts and Associated Economic Damages, Washington, DC, 27–28 January 2011; Session on Socio-economic and Geopolitical Impacts, Friday 28 January 2011, 2:50 pm–3:10 pm

Charge questions

Briefly review existing studies of the impacts of climate change on intra- or inter-regional conflicts, with special attention to any existing quantitative estimates of the effects of changes in temperature, precipitation patterns, or sea level on conflict. Which regions are likely to be the most vulnerable to these impacts?

Briefly review the models and data used to estimate these impacts. What factors are most important to capture in such models when thinking about the conflict impacts of climate change over a long time frame?

Characterize the uncertainty/robustness/level of confidence in these estimates, globally and by region. What are the most important gaps or uncertainties in our knowledge regarding the conflict impacts of climate change? What research in this area would be most useful in the near term?

Abstract

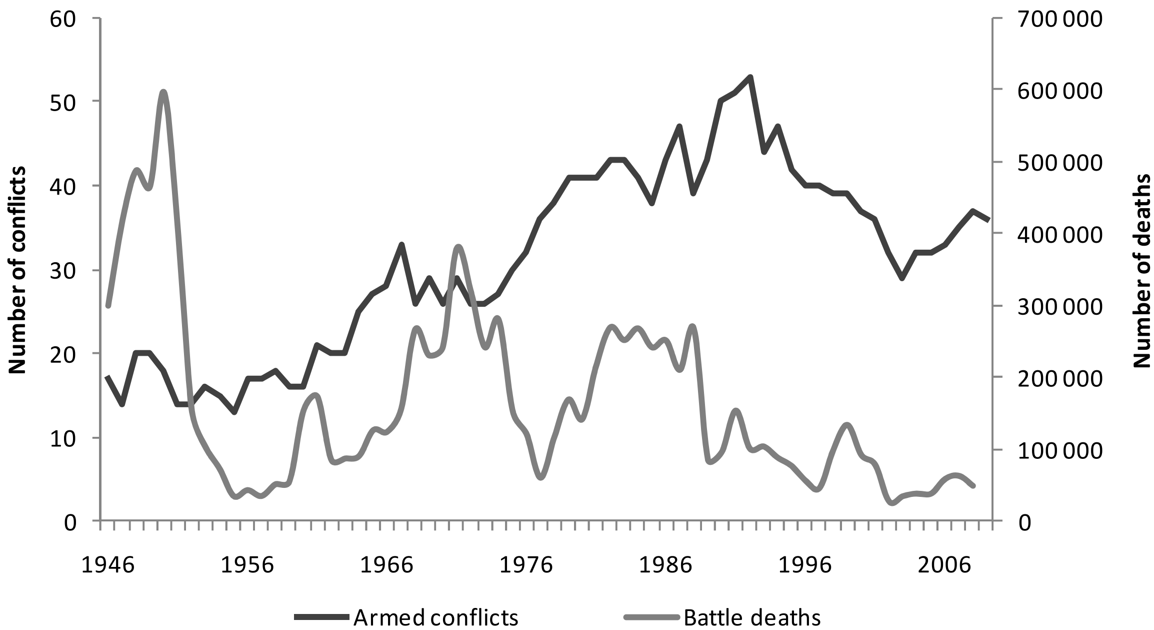
The world is generally becoming more peaceful, but the debate on climate change raises the specter of a new source of instability and conflict. In this field, the policy debate is running well ahead of its academic foundation – and sometimes even contrary to the best evidence. To date there is little published systematic research on the security implications of climate change. The few studies that do exist are inconclusive, most often finding no effect or only a low effect of climate variability and climate change. The scenarios summarized by the Inter-Governmental Panel on Climate Change (IPCC) are much less certain in terms of the social implications than the conclusions about the physical implications of climate change, and the few statements on the security implications found in the IPCC reports are largely based on outdated or irrelevant sources. This paper reviews briefly the models and the uncertainties and outlines some priorities for future research in this area.

* This paper builds on various publications from the Centre for the Study of Civil War at PRIO including Buhaug (2010a), Buhaug, Gleditsch & Theisen (2008, 2010), Gleditsch & Nordås (2009), Gleditsch, Nordås & Salehyan (2007), and Nordås & Gleditsch (2007b). I am grateful to my colleagues Halvard Buhaug and Ole Magnus Theisen for comments and suggestions. Our research is principally funded by the Research Council of Norway. Author address: Centre for the Study of Civil War, PRIO, P. O. Box 9229, Grønland, 0134 Oslo, Norway; nilspg@prio.no.

Introduction

A liberal peace seems to be in the making (Gleditsch, 2008), with a decreasing number of armed conflicts (Gleditsch et al., 2002; Harbom & Wallensteen, 2010) and lower severity of war as measured by annual battle-related deaths (Lacina, Gleditsch & Russett, 2006; HSRP, 2010). At the same time, there has been a strong in democracy, trade, international economic integration, and memberships in international organizations, as well as in international peace-keeping and mediation efforts. Figure 1 illustrates the trends in the frequency and severity of armed conflict.

Figure 1. The frequency and severity of armed conflict, 1946–2009



Source: UCDP/PRIO Armed Conflict Dataset, v. 4–2006 (Gleditsch et al., 2002) and PRIO Battle Deaths Dataset, v. 2.0 (Lacina & Gleditsch, 2005). Figure created by Halvard Buhaug. Data available from www.prio.no/cscw/datasets and www.pcr.uu.se/research/UCDP/. The figure includes all state-based conflicts with more than 25 battle deaths in a calendar year.

The financial crisis, fundamentalist religion, and other factors are widely seen as obstacles on the road towards a more peaceful world. But the greatest challenge to the global liberal peace, according to an increasingly widespread view, is the threat of climate change. Fears on this score have been expressed by the Norwegian Nobel Committee (Mjøs, 2007), which awarded the Nobel Peace Prize for 2007 to Al Gore and the Inter-Governmental Panel for Climate

Change and by President Barack Obama (2009). The UN Security Council discussed the security implications of climate change for the first time in April 2007 (UN, 2007).

Despite the rhetoric, there is little systematic evidence to date that long-term climate change or short-term climate variability has had any observable effects on the pattern of conflict at any level. The Intergovernmental Panel on Climate Change (IPCC) is the main source of scientific information on the causes and consequences of climate change and has had a strong influence on the agenda of the public debate. However, so far the IPCC has not made the security implications a priority issue. The Third and Fourth Assessment Reports (IPCC, 2001, 2007) make scattered comments on climate change in the reports from Working Group II on 'Impacts, Adaptation, and Vulnerability', but these comments are very weakly founded in peer-reviewed research. There is no thematic chapter for security or conflict, so the scattered comments turn up in chapters on other topics such as freshwater management and in some of the regional chapters (notably in the Africa chapter of AR4).

Had the IPCC systematically reviewed the conflict literature, it would have discovered some relevant research relating to scarcity models of conflict. And since 2007, more systematic research on the security implications effects of climate change has emerged. In what follows, I will review this literature, assess the level of uncertainty of this area of research (which is high), and discuss priorities for future research. But first, a brief primer on conflict.

Defining conflict[2]

In our research, we distinguish between conflict, understood as an incompatibility between actors over interests or values, and conflict behavior. Although for convenience, the literature often refers just to 'conflict', we are interested in *armed conflict,* defined by the Uppsala Conflict Data Program (UCDP) as a contested incompatibility that concerns government or territory or both where the use of armed force between two parties results in at least 25 battle-related deaths in a calendar year. Of these two parties, at least one is the government of a state. A war is defined as an armed conflict with more than 1,000 battle-deaths in a calendar year. UCDP's Armed Conflict Dataset (ACD) has been compiled for the time-period 1946–2009 (Harbom & Wallensteen, 2010) and is updated annually. To distinguish them from other types of armed conflict, such conflicts are now frequently referred to as *state-based armed conflict.* They can be subdivided into *interstate conflict* (between two or more states), *extra-state*

[2] Detailed definitions from the Uppsala Conflict Data Program are found at www.pcr.uu.se/research/ucdp/definitions.

conflict (between a state and a non-state group outside its own territory, e.g. colonial war), *intrastate conflict* (between the government of a state and internal opposition groups), and *internationalized intrastate conflict* (where troops from another country supports one or both parties to the conflict). The term *civil war* is used for intrastate armed conflict with more than 1,000 battle deaths.

Two additional forms of conflict, both with the same lower threshold of 25 battle deaths in a calendar year and covering the period 1989–2008, are now regularly recorded by the UCDP, although not necessarily updated annually[3]: *One-sided violence* is the use of armed force by the government or an organized group against civilians. This dataset, which covers the period 1989–2009, includes genocide and politicide. *Non-state conflict* is the use of armed force between two organized armed groups, neither of which is the government. This includes communal violence. A final form of violence, not coded as a separate category by UCDP, is *Riots,* rural or urban, where the violence is not carried out by an organized group, and where the target is mostly the government but which can also be directed against private actors. A borderline case is *violent crime,* which often accompanies riots and even organized violence and sometimes can be hard to separate from violent conflict (Collier, 2000).

Of the different types of conflict, disregarding crime, interstate conflict and one-sided violence claimed the greatest numbers of lives in the twentieth century. Civil war follows next, while communal conflicts and riots are usually smaller. Given the small number of interstate wars after the end of the Cold War and the sparsity of major episodes of one-sided violence, civil war is now the main killer.

The political rhetoric is unclear about the kinds of conflict expected to result from climate change, but all these forms of violence have been mentioned at times. The academic work on the topic needs to be more specific, and many scholars expect climate change to have a greater impact on non-state violence than on state-based conflict.

The term 'regional conflict' in the assigned title for this talk is interpreted in the first charge question as 'intra- or inter-regional conflict'. The common meaning of regional conflict is probably conflict within certain regions.[4] In fact, a large share of the emerging research focuses on Sub-Saharan Africa as the most probable venue for climate-induced violence. The alternative interpretation, conflict between regions, would potentially involve violence at a higher

3 The data can be downloaded from www.pcr.uu.se/research/ucdp/datasets/.

4 See, for instance, an early discussion of environmental quality (including climate change) and regional conflict (Kennedy et al., 1996).

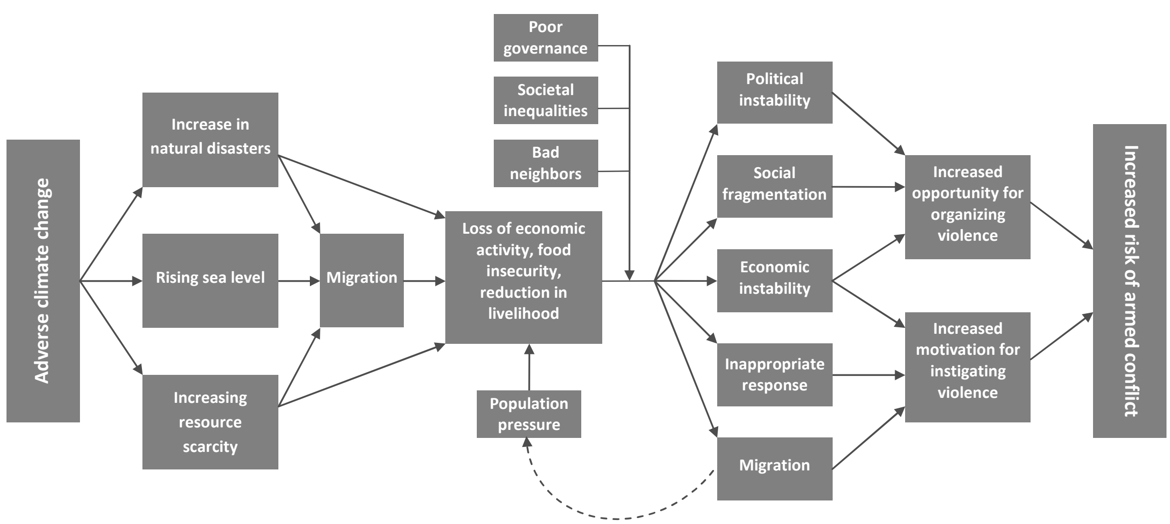
level, possibly even 'world war'. Most of the research discussed here is relevant to the first interpretation, but I will also pay brief visits to interregional conflict.

Linking climate change to conflict

Figure 2 is a theoretical model linking climate change to intrastate armed conflict. The model incorporates insights from case studies as well as statistical studies of conflict. Three effects of climate change (natural disasters, sea-level rise, and increasing resource scarcity) are posited to lead to loss of livelihood, economic decline, and increased insecurity either directly or through forced migration. Interacting with poor governance, societal inequalities, and a bad neighborhood, these factors in turn may promote political and economic instability, social fragmentation, migration, and inappropriate responses from governments. Eventually this produces increased motivation for instigating violence as well as improved opportunities for organizing it.

In the following we review the evidence for some of these links via the three mechanisms mentioned in Charge question 1 (precipitation, temperature, and rising sea level) as well as two others (natural disasters and arctic rivalry) that are frequently mentioned in the literature.

Figure 2. Possible pathways from climate change to conflict



The diagram gives a synthesized account of proposed causal linkages between climate change and armed conflict. For the sake of clarity, possible feedback loops, reciprocal effects, and contextual determinants are kept at a minimum. Source: Buhaug, Gleditsch & Theisen (2008: 21).

Evidence

Only a limited number of peer-reviewed studies deal with climate change/variability and conflict. In the following, I include a few unpublished papers in the discussion. These are generally papers that have been circulating in the academic community for some time, have been revised, and are currently under review at major journals or in press.

Precipitation

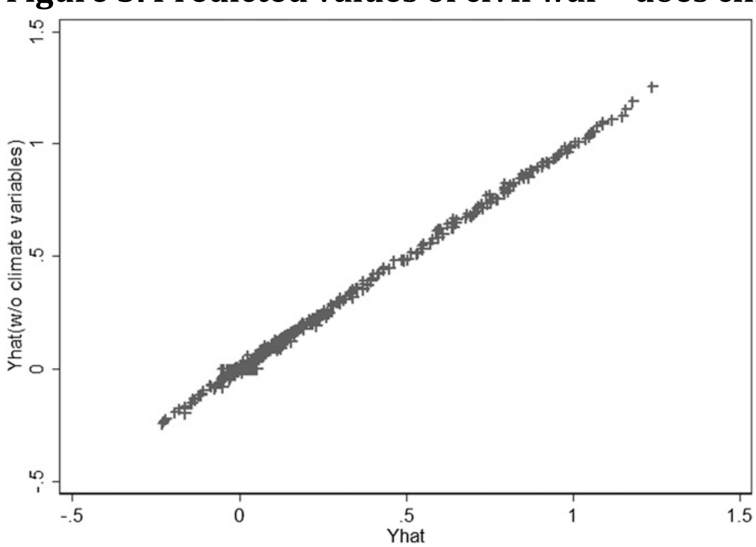
The scarcity (or neo-malthusian) model of conflict assumes that if climate change results in a reduction in essential resources for livelihood, such as food or water, those affected by the increasing scarcity may start fighting over the remaining resources. Alternatively, people may be forced to leave the area, and create new scarcities when they encroach on the territory of other people who may also be resource-constrained. Barnett & Adger (2007) review a broad range of studies of both of these effects, focusing particularly on countries where a large majority of the population is still dependent on employment in the primary sector. If climate change results in reduced rainfall and access to the natural capital that sustains livelihoods, poverty will be more widespread and the potential for conflict greater. Published statistical studies of conflicts globally (Raleigh & Urdal, 2007) or in Africa (Hendrix & Glaser, 2007; Meier, Bond & Bond, 2007) provide only limited support for these hypotheses. For instance, Raleigh & Urdal concluded (p. 674) on the basis of local-level data, that the effects of land degradation and water scarcity were 'weak, negligible, or insignificant'. Many of these early studies were inspired by a study by Miguel, Satyanath & Sergenti (2004), which found a relationship between negative rainfall deviation and increased risk of civil war in Africa. These authors were not primarily interested in climate change, but used rainfall deviation as an instrument for economic shocks. Jensen & Gleditsch (2009) have pointed out that Miguel et al. misinterpreted the UCDP data and included countries that intervene in civil war as countries at civil war. Correcting for this, their results are weaker. And as Ciccone (2010) has remarked, Miguel et al. look only at year-to-year rainfall deviations rather than deviations from a long-term mean. Using this indicator, which better reflects abnormality in rainfall and conforms more closely to the idea of climate change, their results evaporate. All of these studies are conducted at the national level. But rainfall variations do not follow national boundaries. Theisen, Holtermann & Buhaug (2010) used disaggregated data on conflict and climatic variations and found no relationship at the local level. Looking at a broader set of conflicts for the past two decades, Hendrix &

Salehyan (2010) found rainfall to be correlated with civil war and insurgency, but it is wetter years that are more likely to suffer from violent events. Extreme deviations in rainfall – particularly dry and wet years – are associated with all types of political conflict.

Temperature

Two of the authors behind Miguel et al. (2004) were also involved in a more recent study of temperature and conflict. In a widely publicized study, Burke et al. (2009, 2010) claimed to find a link between temperature and civil war in Sub-Saharan Africa for the period 1981–2002 and argued that over a 35-year period climate change would produce a major increase in the incidence and severity of civil war in the region, despite the expected conflict-dampening effect of economic growth and continued democratization during this period.[5] However, Buhaug (2010a,b) found that their results were not robust to standard control variables, to variations in the model specification, to different cut-offs for the severity of conflict, or to an extension of the time series to the most recent years. Buhaug concluded that climate variability is not a good predictor of civil war. Instead, civil war can be better accounted for by poverty, ethno-political exclusion, and the influence of the Cold War. Figure 3 from Buhaug's work indicates that using one of the models from Burke et al. (2009), the climate variables (temperature and precipitation) add virtually nothing to the explanatory power of the model.

Figure 3. Predicted values of civil war – does climate matter?



[5] They also suggest (Burke et al., 2009: 20672) that 'earlier findings of increased conflict during drier years' may have captured the effect of temperature and that 'the role of precipitation remains empirically ambiguous'

This figure plots predicted values of civil war for Model 2 of Burke et al. (2009) on the horizontal axis and a similar model without climate parameters on the vertical axis (r=.999). The linear models predict outside the range of possible values (0,1). The climate variables add 0.002 to a total explained variance of 0.657. Source: Buhaug (2010b: E186–187).

A study that looked at long-term trends (a millennium) in climate and war for China (Zhang et al., 2006) showed that China suffered more often from war, population decline, and dynastic changes during cold periods. A follow-up paper found more that cooling impeded agricultural production, in turn resulting in price inflation, war, famine, and population decline (Zhang et al., 2007) A study of Europe over the last millennium (Tol & Wagner, 2010) found that violent conflict (data from www.warscholar.com/) was more intense during colder periods, but that this relationship disappears in the past three centuries and is not robust to details of the climate reconstruction or to the sample period.[6] It makes sense that by and large a colder climate over some time would lead to a drop in agricultural production and thus in food scarcity and also makes sense that these Malthusian constraints are becoming less important over time with increasing industrialization and long-distance trade But the conflict data have not yet been frequently used in academic research and so far these findings have not been tested by other scholars.

A recent study of Central Europe by Büntgen et al. (2010), while not addressing armed conflict directly, links climate to the rise of fall of civilizations. It confirms the link between warmer summers and improved conditions for human settlements but also finds that climate variability has a major impact. However, the authors concede that modern societies may be less vulnerable to climatic fluctuations.

Several decades ago there was widespread concern in the scientific community that the world might be facing a period of global cooling, possibly even a new ice age. The CIA warned of an era of drought, famine, and political unrest, and even a potential for international conflict. The agency's analysis suggested that forecasting climate was vital to the planning and execution of US policy and would occupy a major portion of US intelligence assets (CIA, 1974).

A long line of research links hot temperatures to individual aggression, including violent crime and riots. Anderson (2001) suggests that therefore global warming may increase violence. But the causal mechanism proposed in

[6] The positive correlation between low temperature and conflict holds for most of Europe, but in the Balkans it is reversed. However, they note that the Balkans is largely excluded from the conflict database. They also report a positive correlation between precipitation and conflict for most of Europe in the earlier centuries (which they attribute to a decline in agricultural output due to waterlogging) and a negative correlation in the Balkans (which may be due to drought). Again, this correlation is not found for the most recent three centuries.

these studies (personal discomfort) is different from the scarcity thesis that is at the core of the relationship proposed by Burke et al. (2009) and the kind of violence is also different.

Sea-level change

IPCC (2007, WG II: 323) forecasts a global mean sea-level rise of between 0.28 and 0.43 meters within this century, depending on the scenario chosen.[7] Projections for the size of coastal populations (residing below 100 m elevation and less than 100 km from the coast) show that they may rise from 1.2 billion (1990 estimate) to between 1.8 and 5.2 billion (Nicholls & Small, 2002). Sea-level rise will threaten the livelihood of the populations on small island states in the Indian Ocean, the Caribbean, and the Pacific. However, a much larger number of people in low-lying areas, rural and urban, and particularly in South Asia and West Africa, may become more exposed to soil erosion, seasonal flooding, and extreme weather. Depending on the degree of protection that can be offered, this may lead to 'climate migration', and conflict with the host population is a possible consequence (Nicholls & Tol, 2006). However, this is going to be a slow process and urbanization and industrialization may well absorb a large fraction of the people who move.

In a global study covering the period 1951–2001, Salehyan & Gleditsch (2006) found that an influx of refugees increased the probability of civil war. However, since a large proportion of these people have fled from conflict, they are likely to bring with them the attitudes, the weapons, and the organization that fuel a continuation of the conflict in the host location. It is not obvious that economic migrants, including environmental migrants, will generate armed conflict in the same way (Gleditsch, Nordås & Salehyan, 2007). However, this has not been studied systematically, due to conceptual problems (what is the definition of an environmental migrant?) and lack of systematic data. Reuveny (2007) examined 38 cases of environmental migration since the 1930s and found that in half of them there was some kind of armed conflict, most frequently when the migration cross international boundaries. While suggestive, his study is unlikely to include all cases of environmental migration during this period and the conflicts are of different types. Moreover, he did not have any control variables.

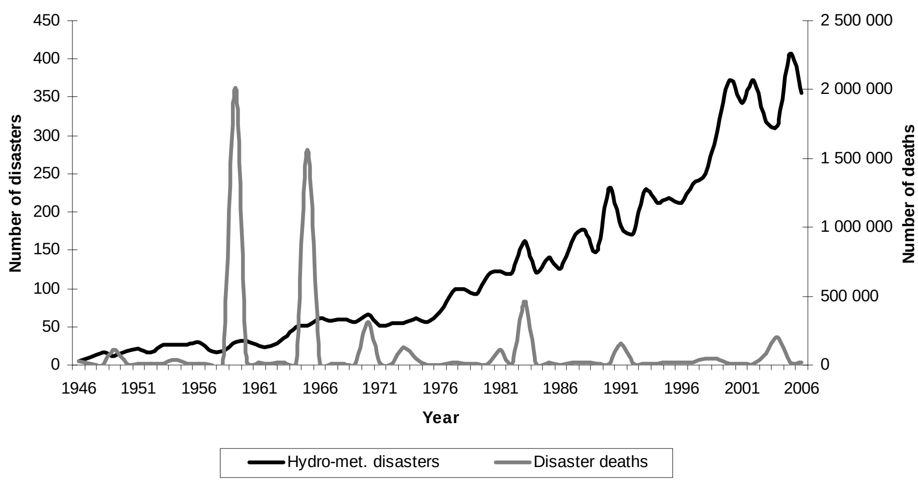
[7] Several more recent estimates are higher, cf. Grinsted, Moore & Jevrejeva (2009) who project sea-level rise to the end of the twenty-first century from 0.9 to 1.3 m for the A1B scenario.

Natural disasters

Global warming is predicted to increase the frequency and intensity of natural disasters such as tropical storms, flash floods, landslides, and wild fires, and substantially alter precipitation patterns in many parts of the world. There has been a sharp increase in the number of disasters over the last sixty years[8], although it is not certain how much of this can be accounted for by improved reporting, population growth, and shifting patterns of settlement. In 2009, 335 natural disasters were reported, killing more than 10,000 people (Vos et al., 2010: 1). Asia is the region most heavily affected. Geological disasters like volcanic eruptions, earthquakes, and tsunamis need not concern us here, since they are unlikely to be influenced by climate change. The temporal increase in disaster frequency is largely accounted for by hydrological and meteorological disasters, particularly by floods, as shown in Figure 4.

The severity of disasters, measured as the number of casualties, shows no evident time trend, presumably because of increasing coping capacity in many countries. Future economic development is likely to further increase the ability of many societies to absorb natural disasters without great loss of human life, so an increase in extreme weather events need not be accompanied by higher casualty figures. Geological events are slightly more deadly, but the more numerous climate-related generate the highest overall death toll.

Figure 4. Frequency and severity of hydro-meteorological disasters since 1946



[8] Vos et al. (2010: 5) define a disaster as 'a situation or event which overwhelms local capacity, necessitating a request to a national or international level for external assistance; an unforeseen and often sudden event that causes great damage, destruction and human suffering'.

Source of Figure: Buhaug, Gleditsch & Theisen (2008: 11). Data from EM-DAT, Centre for Research on the Epidemiology of Disasters (CRED). An update from CRED (Vos et al., 2010) does not show any time trend in the number of disasters for the most recent decade.

Natural disasters may exacerbate conflict risk primarily through economic loss and a weakening of government authority. Some statistical studies find the risk of conflict to be higher following natural disasters (Drury & Olson, 1998; Brancati, 2007; Nel & Righarts, 2008).[9] However, Slettebak & de Soysa (2010), drawing on a long tradition in disaster sociology, argue that disasters are just as likely to unite those who are adversely affected, at least in the short run, implying that various forms of anti-social behavior, including violence, should decline. Using a global sample from 1950 until today and a set of standard control variables they find that countries affected by climate disasters face a lower risk of civil war. Similarly, Bergholt & Lujala (2010) find that climatic natural disasters such as floods and storms have a negative impact on economic growth but have no effect on the onset of conflict, either directly or as an instrument for economic shocks.

Arctic rivalry

The melting of the Arctic icecap has been predicted to lead to a scramble for shipping lanes and natural resources in previously inaccessible territories (Borgerson, 2008; Paskal, 2010). Since there is no established legal regime for the region, some observers feel that this could lead to armed conflict. Several major powers have interests in the region, so potentially this could lead to some serious conflicts. On the other hand, the vast extension (from the early 1970s) of national sovereignty through the establishment of Exclusive Economic Zones (EEZs) points in a different direction. Despite legal action, unresolved boundaries, and occasional confrontations, particularly over fisheries, the establishment of EEZs to 200 miles off the coastline has proceeded in overwhelmingly peaceful fashion. Although several countries (including the US) have not ratified the UN Convention on the Law of the Sea (concluded in 1982, entered into force in 1994), its provisions are generally respected. Most observers seem to agree with Haftendorn (2010) that a mad race to the Pole is not very likely, nor is a military conflict among the contenders. Historically, the role of disputed territory is one the central issues of war (Holsti, 1991; Huth, 1996) but interstate war, regardless of issue, has declined to the point where it is now very rare (Harbom & Wallensteen, 2010).

[9] Brancati (2007) studied only earthquakes and Nel & Righarts (2008) also found stronger results for geological than for climatic disasters.

Vulnerable regions

Which are the most vulnerable regions? Empirical studies of rainfall and temperature (such as Miguel et al., 2004; Burke et al., 2009, Buhaug, 2010) have largely focused on Africa South of Sahara. In part, this is because Africa is more dependent on rain-fed agriculture and thus more severely affected by major climate change or variability. But it is also because climate change is expected to be associated with conflict in interaction with other conflict-inducing factors, such as poverty, economic decline, ethnic exclusion etc. (Buhaug, Gleditsch & Theisen, 2010), all of which also have been frequent in Africa. Of the 58 countries included in the 'bottom billion' (the countries that are both poor and stagnating) close to two-thirds are found in Africa (Collier, 2009).

Africa is also one of the more conflict-prone regions, along with South Asia and the Middle East. In the late 1990s, Africa accounted for more battle-related deaths than all other regions together. However, since then, all regions – and Africa in particular – have experienced a decline in battle deaths. Since 2005 most battle deaths have occurred in Central and South Asia, driven in particular by the wars in Sri Lanka, Afghanistan, and Pakistan.

In the second half of the twentieth century, East Asia experienced the three largest wars anywhere, the Chinese Civil War, the Korea War, and the Vietnam War, However, since the Vietnamese invasion of Cambodia in 1978 and the Sino-Vietnamese War in 1979 (followed by some minor skirmishes in the 1980s), this region has been largely free of war.[10]

Since the physical effects of climate change are so varied, it is hard to compare regions in terms of the overall effects of climate change. IPCC (2007, WG II: 435) characterizes Africa as 'one of the most vulnerable continents to climate change and climate variability', but this judgment is made as much because of Africa's low adaptive capacity as much as the absolute size of the climate changes.

Unfortunately, the climate change projections for Africa are highly uncertain (IPCC, 2007, WG I: 266ff.). Paradoxically, where accurate measurement of historical climate variables is the most needed, the information is also the most limited.

[10] Cf. www.prio.no/cscw/cross/battledeaths. The major exception is provided by the two insurrections in the Philippines, which have claimed some than 20,000 battle deaths over this thirty-year period. By contrast, each of the three major East Asian wars claimed more than one million battle deaths each over much shorter time periods.

Major climate change challenges in Asia include possible increased seasonal flooding and drought in the areas downstream from the shrinking Himalayan glaciers, environmental refugees following sea-level rise, and threats to major coastal cities such as Dhaka, Mumbai, and Hong Kong as a result of increased tropical storms as well s sea-level rise (IPCC, 2007; Wischnath, 2010). These challenges are particularly serious since the population of Asia makes up more than half of the world total. On the other hand, economic growth has been particularly rapid in large parts of Asia in the past two decades, so the adaptive capacity is clearly larger than in Africa.

Models

The climate models used in studies of the effects on conflict are generally derived from standard sources, such as those used by the IPCC. For instance, Burke et al. (2009) use time series on precipitation and temperature from the Climatic Research Unit at the University of East Anglia and climate projections from general circulation models from the World Climate Research Program's Coupled Model Intercomparison Project under the IPCC's A1B emissions scenarios, with some alternative calculations under the A2 and B1 scenarios. Although different scenarios yield somewhat different results, current controversies about the effects of climate change on conflict do not seem to depend on the choice of historical data or emissions scenarios.

There is no standard model of conflict which is universally accepted, but the two most frequently used models of civil war are those used in Fearon & Laitin (2003) and Collier & Hoeffler (2004), and Hegre & Sambanis (2006) have conducted a sensitivity analysis to identify the most robust variables from a large number of common explanatory schemes. Buhaug (2010a) employs some of the variables from these studies as controls and alternative explanations. Burke et al. (2010), however, insist that controlling for endogenous variables, i.e. independent variables that can be influenced by conflict (or the anticipation of it) will bias the analysis. In the early work of Miguel et al. (2004) the endogeneity problem was tackled by using rainfall deviation as an instrument for economic shocks, but it is not always possible to find suitable instruments and in Burke et al. (2009) there are none.

As already shown in Figure 3 above, the climate variables add very little to the explanatory power of the model used by Burke et al. (2009). The relatively high explanatory power, with R^2 as high as 0.66 in their Model 1, is driven by the fixed country effects and the time trends. Standard opportunity models of civil war, such as Fearon & Laitin (2003) and Collier & Hoeffler (2004) as well as studies that place more emphasis on ethnic grievances, such as Cederman &

Girardin (2007), explain more of the variance with explanatory variables and control variables. However, as Ward, Greenhill & Bakke (2010) point out, such models nevertheless do a very poor job of prediction. The Fearon & Laitin (2003) model does not correctly predict a single onset of civil war, while the Collier & Hoeffler (2004) model correctly predicts 3, at the expense of predicting 5 false positives.[11] At the moment, social scientists are poorly equipped to predict rare events like conflict but climate change is just one of many areas where policy prescriptions are dependent on more successful efforts at prediction (Schneider, Gleditsch & Carey, 2010).

Uncertainty

The IPCC assessment reports employ quantitative as well as qualitative assessments of uncertainty. In the Fourth Assessment Report, each Working Group used a different variation. Working Group I, which assessed the physical science, relied primarily on a quantitative likelihood scale, with 'virtually certain' (>99% probability of occurrence) at the top.[12] For instance, WG I estimated it to be 'very likely' (i.e. > 90%) that the frequency of heavy precipitation events would increase in the future for most areas.[13] WG2 relied mostly on a quantitative confidence scale, where e.g. 'high confidence' indicates an 80% or higher chance of being correct.[14] WG III relied exclusively on a qualitative level-of-understanding scale.

The uncertainties in the IPCC assessments are exacerbated by the inclusion of non-peer reviewed material. The basic principle is that material used by IPCC and included in the assessment reports should be peer-reviewed. In WG I on the physical consequences of climate change, this provides the bulk of the evidence. However, the IPCC has concluded that 'it is increasingly apparent that materials relevant to IPCC Reports, in particular, information about the experience and practice of the private sector in mitigation and adaptation activities, are found in sources that have not been published or peer-reviewed' (IPCC, 1999/2008: Annex 2). Each such source is to be critically assessed by the authors of the IPCC assessment and will be archived and made available to IPCC review authors who request them. An outsider cannot know exactly how these guidelines have been used in the preparation of the Third and Fourth Assessment Report, but it is obvious to a reader who knows the

[11] When the threshold is set at p (onset) > 0.5. With a lower threshold, both models predict more conflicts correctly, but they yield an even larger number of false positives (from two to four as many as the correct predictions).
[12] IPCC (2007, WG I: 23), IAC (2010: 29).
[13] IPCC (2007, WG I: 8).
[14] IPCC (2007, WG I: 22), IAC (2010: 28).

literature that a number of sources have in fact been used quite uncritically in references to conflict.[15]

Following the discovery of an error in the Fourth Assessment Report[16] that had cited a non-peer reviewed source to back up a an alarmist statement that the Himalayan glaciers were likely to disappear within 35 years, the UN and the IPCC itself asked the InterAcademy Council, an umbrella group of national academies of science in fifteen countries, to review the IPCC's organization and procedures. Although the evaluation report (IAC, 2010) was generally favorable, there were critical comments that the review editors had insufficient authority to ensure that the authors followed up their comments, that Working Group II (which deals with the social consequences of climate change) had overemphasized the negative aspects of climate change, that it had reported high confidence in some statements for which there was little evidence (p. 4), and that the selection of authors for regional chapters often excludes some of the best experts because they don't live in the region (p. 18). The report also noted that peer-reviewed journal articles comprised 84% of the references in Working Group I, but only 59% in WG II and 36% in WG III (p. 19). An implication, not stated explicitly by the IAC, is that the IPCC's statements on the social implications of climate change are less reliable than assessments of the physical basis.

In the Fifth Assessment Report (AR5), scheduled for 2013, there will be a chapter on human security, which it is expected will also include a discussion of violent conflict.[17] This is a promising development. However, the expertise of the group of authors responsible for this chapter leans heavily towards broader aspects of human security rather than conflict. It seems likely that they will produce a more balanced assessment of the literature on climate change and conflict, as the authors have signaled a stronger emphasis on peer-reviewed literature. But it remains to be seen whether this will prevent more extravagant and empirically unsupported statements being made in other chapters of the report and restrain the more dramatic interpretations by NGOs and politicians.[18]

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[15] For a detailed examination, see Nordås & Gleditsch (2009).

[16] And, at about the same time, the leaking of thousands of documents and e-mails from the Climate Research Unit at the University of East Anglia. For a balanced account of the 'Climategate' affair, see Pearce (2010).

[17] However, the scoping document of the AR5, approved in October 2010, does not reveal the contents at this level of detail, cf. www.ipcc.ch/meetings/session32/syr_final_scoping_document.pdf),

[18] The IPCC November 2010 announcement about the Table of Contents and the authors is found at www.ipcc.ch/meetings/session32/inf07_p32_ipcc_ar5_authors_review_editors.pdf, cf. Chapter 12.

Research priorities

Research on the security effects of climate change should focus on interactions between climatic variables and other conflict-inducing factors, to test the notion that climate change can act as a 'threat multiplier' (CNA, 2007: 1).

Secondly, although data and models may be more readily available for rich countries, research on conflict as a possible effect of climate change needs to focus on the poorer parts of the world, where the adaptive capacity is lower today. Of course, some countries in the third world now have high economic growth and are likely to be in a position to absorb greater changes fifty years from now. Therefore, particular attention needs to be paid to countries that are not only poor but also stagnating.

Third, we need to go beyond the state-based violence considered in most statistical studies to date. Much of the case study literature refers to non-state or one-sided violence, but this has hardly been tested in large-n studies. Unfortunately, the time series for these types of conflict data are still quite short, so improved data collection will be a priority.

More work needs to be put into the geographical disaggregation of the effects of climate change since these effects will not follow national boundaries.

Further, the study of climate change and conflict needs to balance the negative and positive effects of climate change. While food production is likely to decrease in some areas, it may increase in others. Although the global net effect of climate change seems likely to be negative, the effects would vary considerably both geographically and by sector.

Finally, if we are to go beyond the simple projection of past changes into the future, we will need a tighter coupling of climate change models and the conflict models. The development of more fine-grained data for the physical effects of climate change, incorporating geographic variation, rates of change, and adaptive measures, will facilitate the scientific interface. But for the moment, it may be more realistic to concentrate on the past impact of climate change. If such research indicates that the link to conflict is weak, efforts to establish projections into the future probably should have lower priority.

Conclusions

Given the potential range and scope of consequences of climate change, it is not surprising that there is widespread concern about its security implications. In part, this concern has been directed at raising awareness about 'environmental security' in a broad sense. Climate change will have many serious effects, particularly transition effects, on peoples and societies worldwide. The hardships of climate change are particularly likely to add to the burden of poverty and human insecurity of already vulnerable societies and weak governments.[19] However, the use of such wider concepts of security must not stand in the way of a focused effort to analyze empirically the possible link between environmental change and violent conflict. Assuming such a link without the necessary evidence may lead peacemaking astray and can eventually also undermine the credibility of the IPCC and the efforts to reach a consensus of knowledge about human-made climate change and a concerted global effort at mitigation and adaptation. The climate-conflict discourse is easily exploited by cynical governments and ruthless rebels who would like to evade any direct responsibility for atrocities and violence and prefer to put the blame on developed countries and their greenhouse gas emissions (Salehyan, 2008).

Finally, what if the academic community were to conclude that climate change has very little impact on armed conflict. Does it matter? It matters a great deal for the credibility of climate change research. Extremely low-probability hazards should not be promoted to major threats under the precautionary principle. For adaptation to climate change, clarifying the conflict effects may also be important. Preventing armed conflict is likely to require countermeasures that are different than preventing biodiversity loss. For the need to mitigate the effects of climate change, however, the effects of climate probably matter very little. There are many other reasons to reduce the human impact on the climate and to prevent global warming from getting out of hand.

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[19] However, Buhaug, Falch, Gleditsch & Wischnath (2010) found that climate change so far has had no greater absolute impact on temperature and precipitation in 'bottom billion' countries in Africa than in other African countries.

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Biographical information

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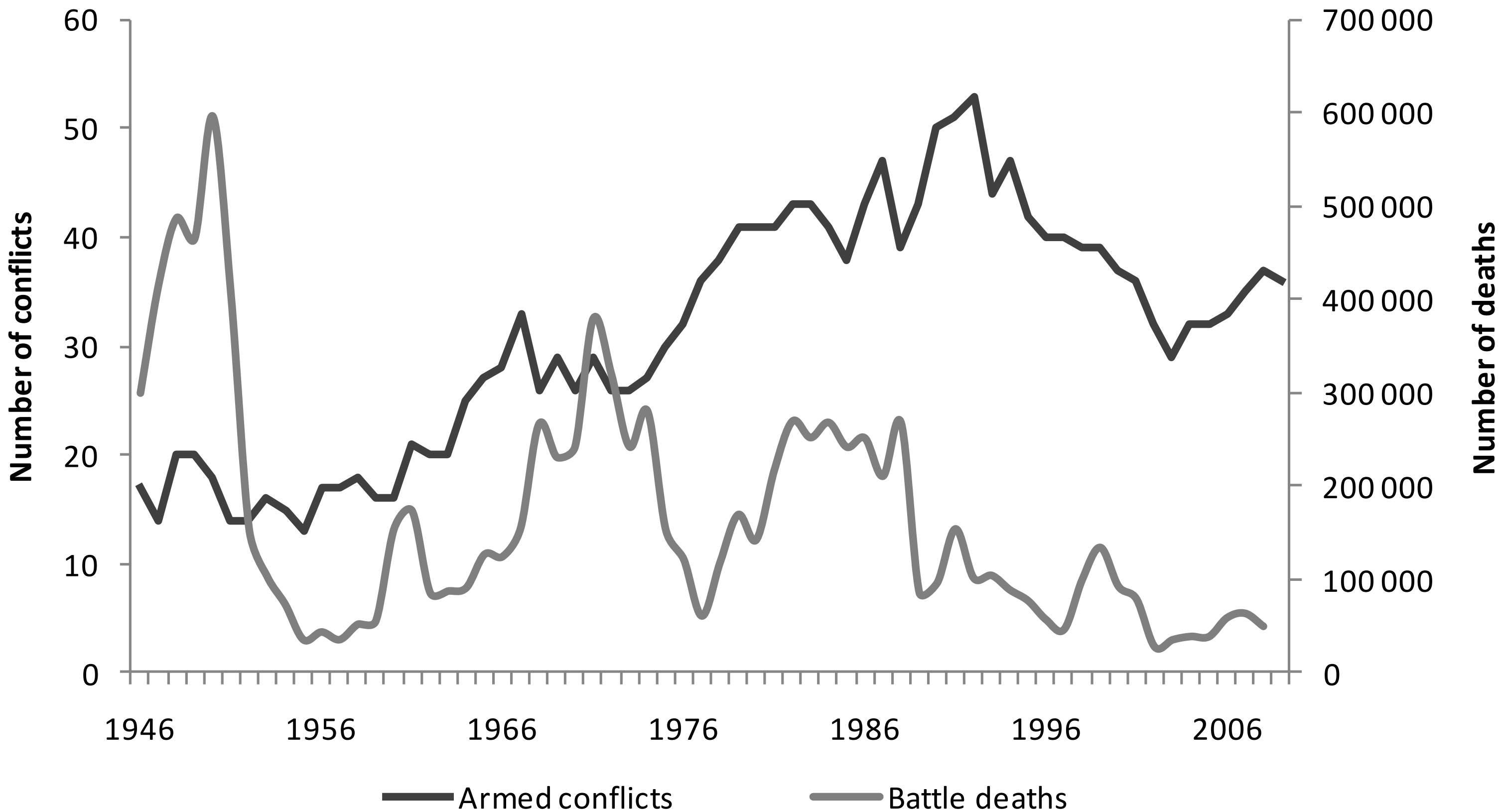
Regional Conflict and Climate change

EPA/DoE workshop on Climate Change Impacts and Associated Economic Damages
Capitol Hilton, Washington, DC, 27–28 January 2011

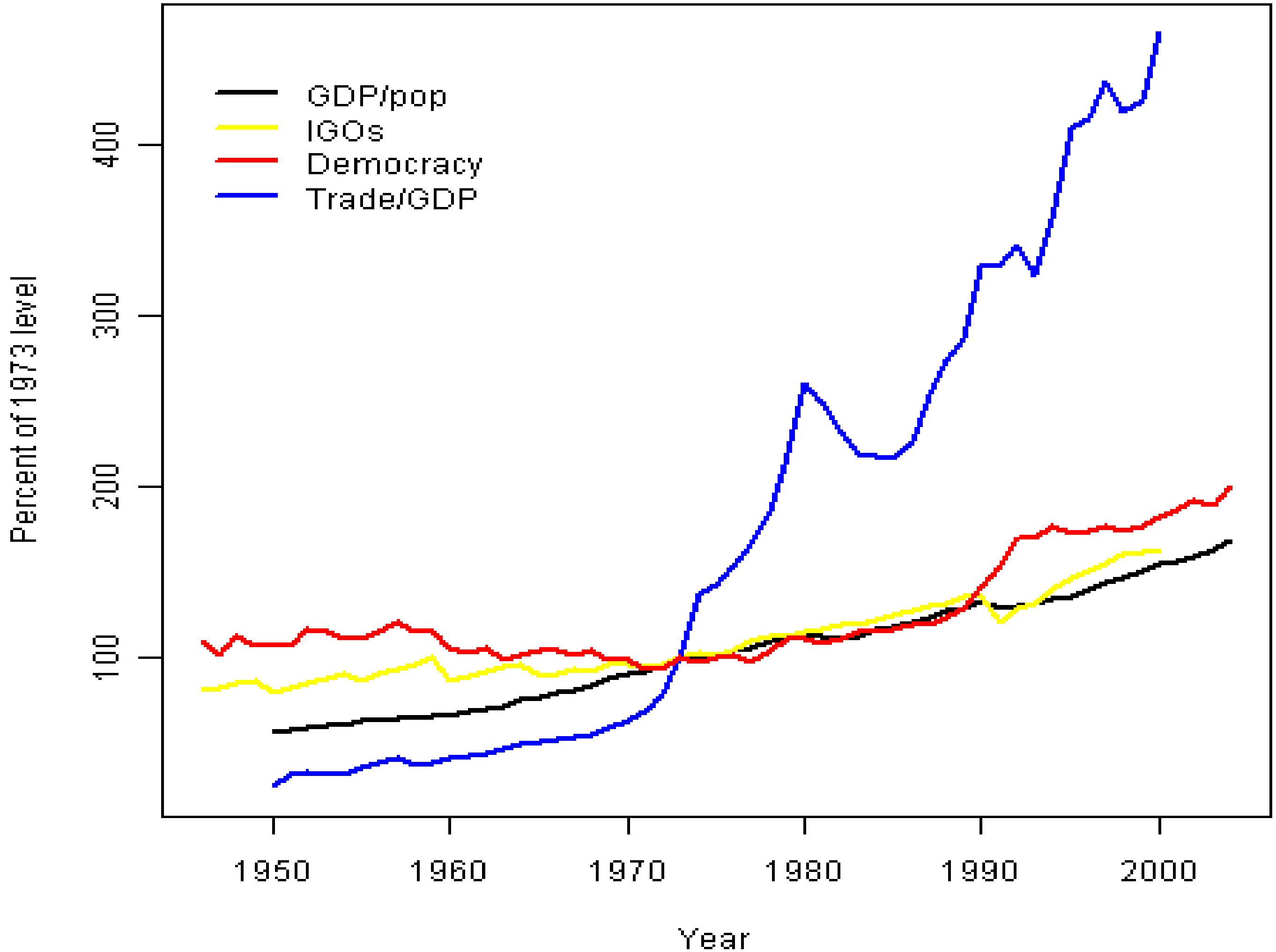
Nils Petter Gleditsch

Centre for the Study of Civil War (CSCW), Peace Research Institute Oslo (PRIO) &
Department of Sociology and Political Science, Norwegian University of Science and Technology (NTNU)

Armed conflicts and battle deaths, 1946–2009



Towards a liberal peace?



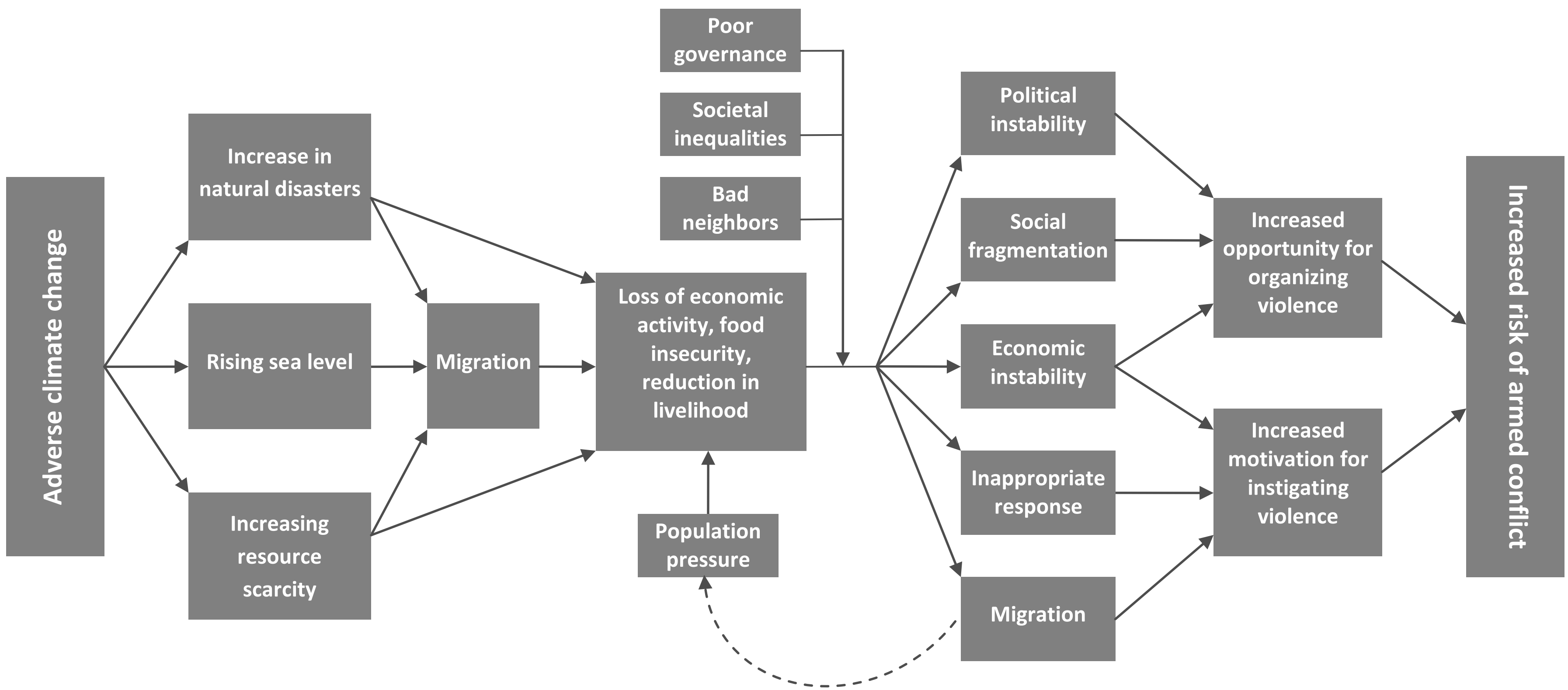
Possible threats to the liberal peace

- Shifting patterns of power
- The financial crisis
- Fundamentalist religion
- Climate change

Enter climate change: Are we heading towards disaster?

- Darfur is the first of many climate wars (Ban Ki-Moon, 2007–08)
- There is little scientific dispute that if we do nothing, we will face more drought, more famine, more mass displacement – all of which will fuel more conflict for decades (President Barack Obama's Nobel Peace Prize Lecture, 10 December 2009)
- Evidence is fast accumulating that, within our children's lifetimes, severe droughts, storms and heat waves caused by climate change could rip apart societies from one side of the planet to the other. Climate stress may well represent a challenge to international security just as dangerous — and more intractable — than the arms race between the United States and the Soviet Union during the cold war or the proliferation of nuclear weapons among rogue states today. (Thomas Homer-Dixon, *NYT,* 24 April 2007)

From climate change to conflict: Possible pathways



Evidence: Precipitation (I)

- *Miguel, Satyanath & Sergenti (2004): the probability of conflict in sub-Saharan Africa increases the year after a year with reduced rainfall (instrument for economic shock)
- *Hendrix & Glaser (2007): the level of available freshwater is positively linked to conflict, but negative deviations also yield more conflict
- *Jensen & Gleditsch (2009): the results in Miguel et al. (2004) are weaker when removing countries that participate in civil wars in other countries

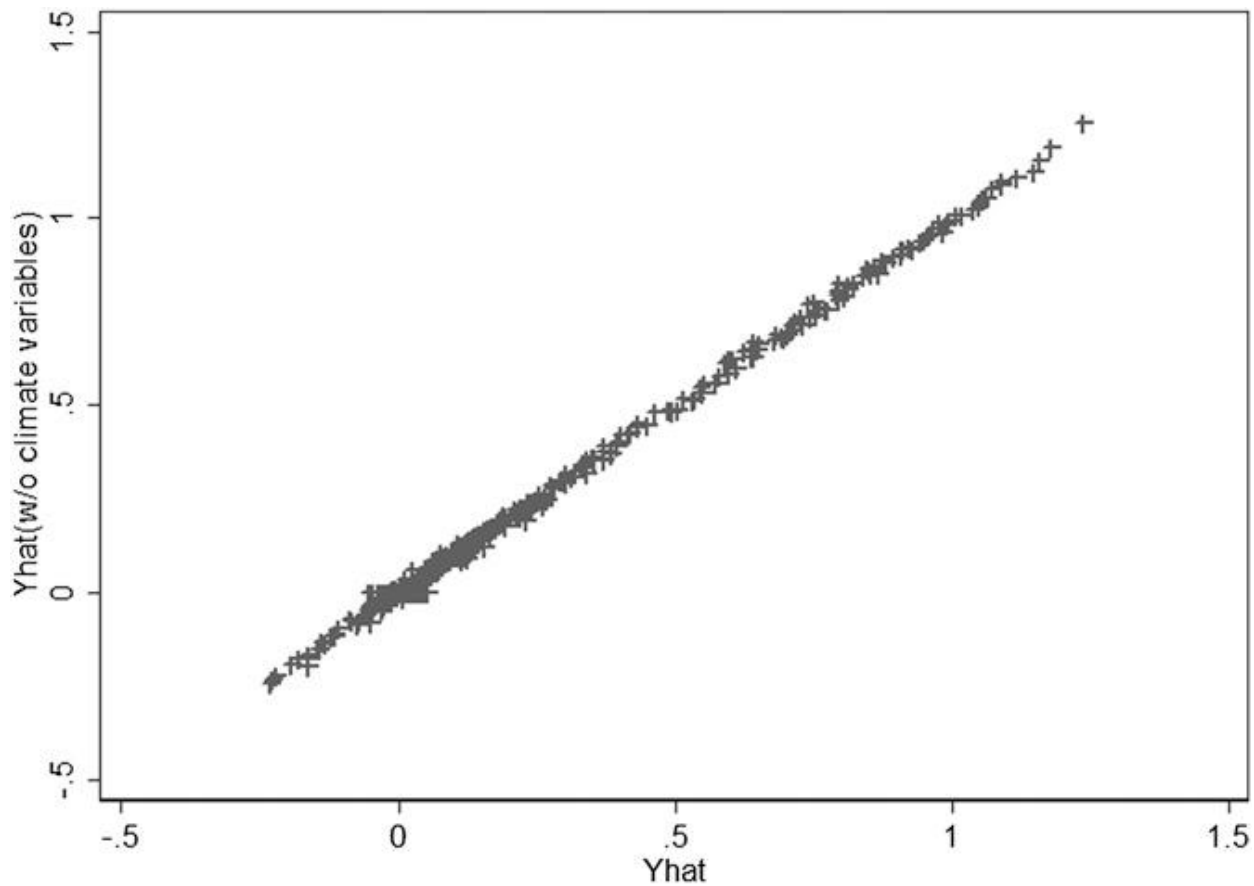
Evidence: Precipitation (II)

- *Hendrix & Salehyan (2010): (47 African countries, 1990–2009) Wetter years are more likely to see civil wars. Rainfall variability has a significant effect on other forms of political unrest.
- Theisen, Holtermann & Buhaug (2010): In a disaggregated analysis, drought has no influence on civil conflict in Africa
- Ciccone (2010): Miguel et al. look only at annual deviations rather than deviations from the long-term mean
- *Burke et al. (2009): Precipitation changes in Africa cannot be predicted precisely from existing climate models

Evidence: Temperature (I)

- *Burke et al. (2009, 2010): Higher temperatures in SS Africa yield more conflict (impact on agriculture);
- *Buhaug (2010a,b) Their results are not robust to standard control variables, to variations in the model specification, or to an extension of the time series to more recent years

Civil war risk with/without climate variables



Evidence: Temperature (II)

- *Zhang (2006, 2007) War, population decline, and dynastic changes were more common in China in cold periods (1000-year time frame)
- *Tol & Wagner (2010) Violent conflict in Europe was more common in cold periods, but the relationship disappears in the most recent three centuries
- *Büntgen et al. (2010) Warmer summers improve conditions for human settlements and the rise of civilizations – but this may be less relevant for modern civilizations
- CIA (1974) Global cooling threatens to produce drought, famine, and political unrest, particularly in the Sahel region. Climate modification could lead to international conflict

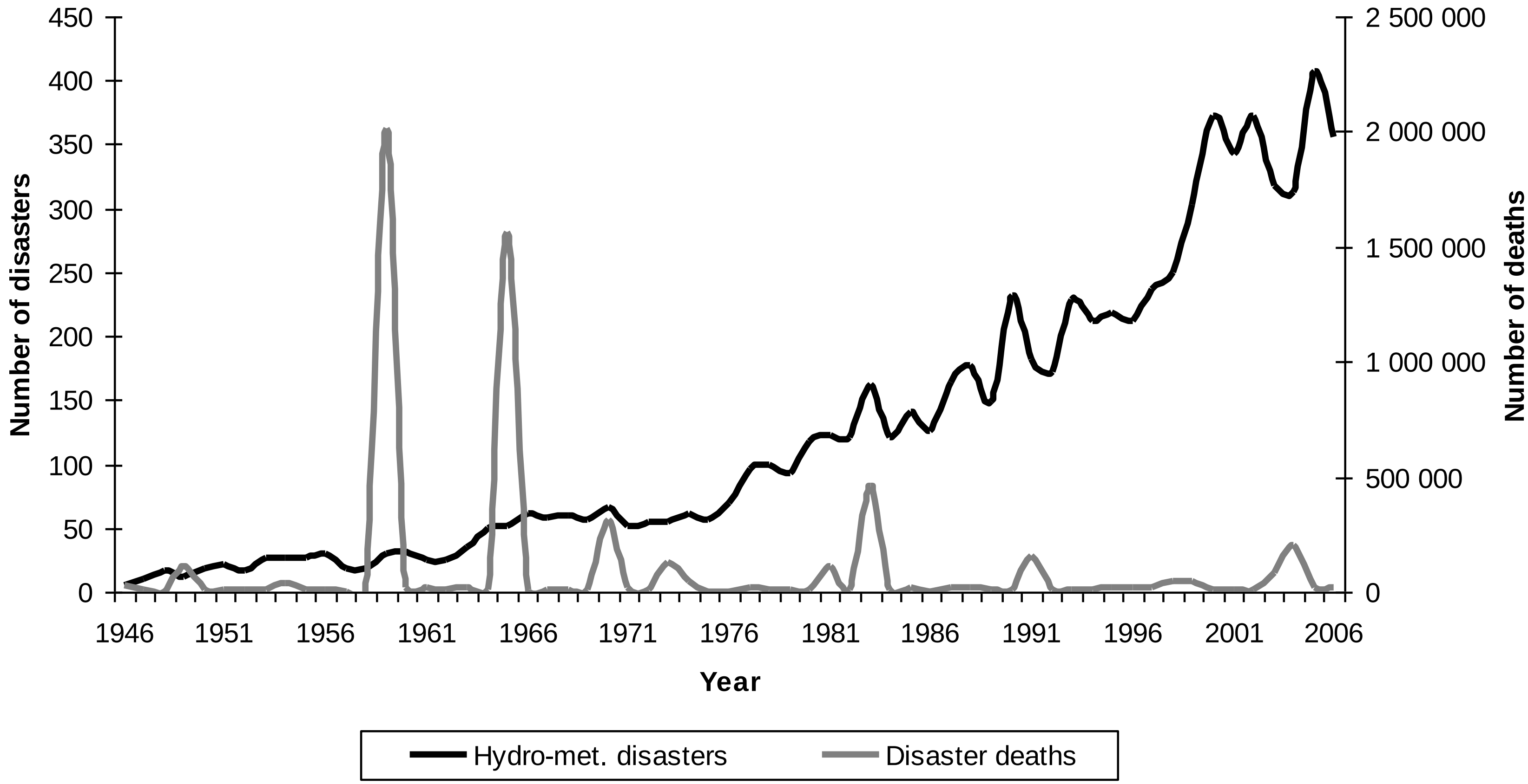
Evidence: Sea-level change

- IPCC (2007, WG II: 323): Global mean sea-level rise to 2100: 0.28-0.43 cm
- *Grinsted, Moore & Jevrejeva (2009): 0.9–1.3 m
- Myers, IPCC, Stern: 150–200–250 mill ‘climate refugees’
- *Nicholls & Small (2002): 1.2 bill. live in coastal areas, rising to 5.2 bill. by the end of the century
- *Salehyan & Gleditsch (2006): Countries with a high influx of refugees have a greater risk of civil war
- Gleditsch, Nordås & Salehyan (2007): Will this also apply to climate refugees?
- *Reuveny (2007): In 38 cases of environmental migration since the 1930s, half experienced armed conflict of some kind – but is this representative?

Evidence: Natural disasters (I)

- CRED data show that the number of natural disasters is increasing, more people affected, fewer people die
- Is the increase in numbers due to global warming, better reporting, shifting settlements?
- Increase in cost, but mainly due to more high-value objects insured?
- Analyses of disasters and conflict suggest a connection (*Drury & Olson, 1998; *Brancati, 2007; *Nel & Righarts, 2008), but mostly for geological disasters, and mechanisms unclear

Hydro-meteorological disasters



Evidence: Natural disasters (II)

- Even for geological disasters, Aceh points in a different direction (*Le Billon & Waizenegger, 2007; *Enia, 2008; *Beardsley & McQuinn, 2009)
- Slettebak & de Soysa (2010): Earlier studies fail to include proper controls, particularly population size. Using the Fearon & Laitin model, climate-related disasters, tend (if anything) to lower the probability of conflict; consistent with a long tradition in disaster sociology that people unite in the face of adversity
- Bergholt & Lujala (2010): Natural disasters lower economic growth but do not increase conflict via this mechanism

Economic effects of climate change

- Economic factors important in conflict – economic interdependence limits interstate conflict, economic development limits intrastate conflict
- Economic decline could reverse this
- Debate about the economic effects of climate change hinges on the value of discounting future economic effects – Stern (2007) uses a low value, while Nordhaus (2007) uses a high value
- Few empirical studies: Bernauer et al. (2010) study effects of precipitation and conflict, Bergholt & Lujala (2010) natural disasters and conflict, neither study finds any effect on conflict via economic growth, but Bernauer et al. find that political institutions modify the relationship

Climate change and interstate conflict

- Argument 1: Increased scarcity → interstate conflict
- Counterargument: Scarcity model generally unpersuasive and less so today
- Argument 2: Climate change will open up new trade routes and new ocean territories for exploration, there will be uncertainty about ownership and competition for exploiting these resources, danger of conflict
- Counterargument: a) little systematic research, b) introduction of EEZs proceeded largely peacefully
- Tir & Stinnett (2010): Institutionalized cooperation in shared rivers is likely to prevent distribution conflicts
- Gartzke (2010): climate change may affect where nations fight, rather than whether or when (militarized disputes move to higher latitudes in summer, lower latitudes in winter)

Methods

- The neomalthusian theory of conflict has generally drawn on case studies for support, notably those by Homer-Dixon and others
- Large-n studies have found little support for the scarcity theories. So is it a methodological divide?
- Several recent case studies, by *Benjaminsen (2008) on Mali, *Witsenburg & Adano (2009) on Northern Kenya, *Brown (2010) on Darfur, and others have also questioned the scarcity perspective
- The neomalthusian case studies in the scarcity tradition have been criticized for selecting on the dependent variable, i.e. studying only the conflict cases
- But they can also be criticized for relatively shallow case description and for focusing too rapidly on scarcity factors
- We may perhaps see a convergence of case studies and statistical work, including time-series for single countries and disaggregated statistical studies

Interactions

Critics of Homer-Dixon and others may have overlooked how scarcity interacts with poverty, poor governance, ethnic dominance, etc.

Threat multiplier (CNA , 2007)

Double exposure (O'Brien), also Temesgen (2010)

'Unfortunately, pollution, population growth and climate change are not in the distant future: they are occurring now and hitting the poorest and most vulnerable hardest. Environmental degradation has the potential to destabilize already conflict-prone regions, especially when compounded by inequitable access or politicization of access to scarce resources.' – Kofi Annan (2006)

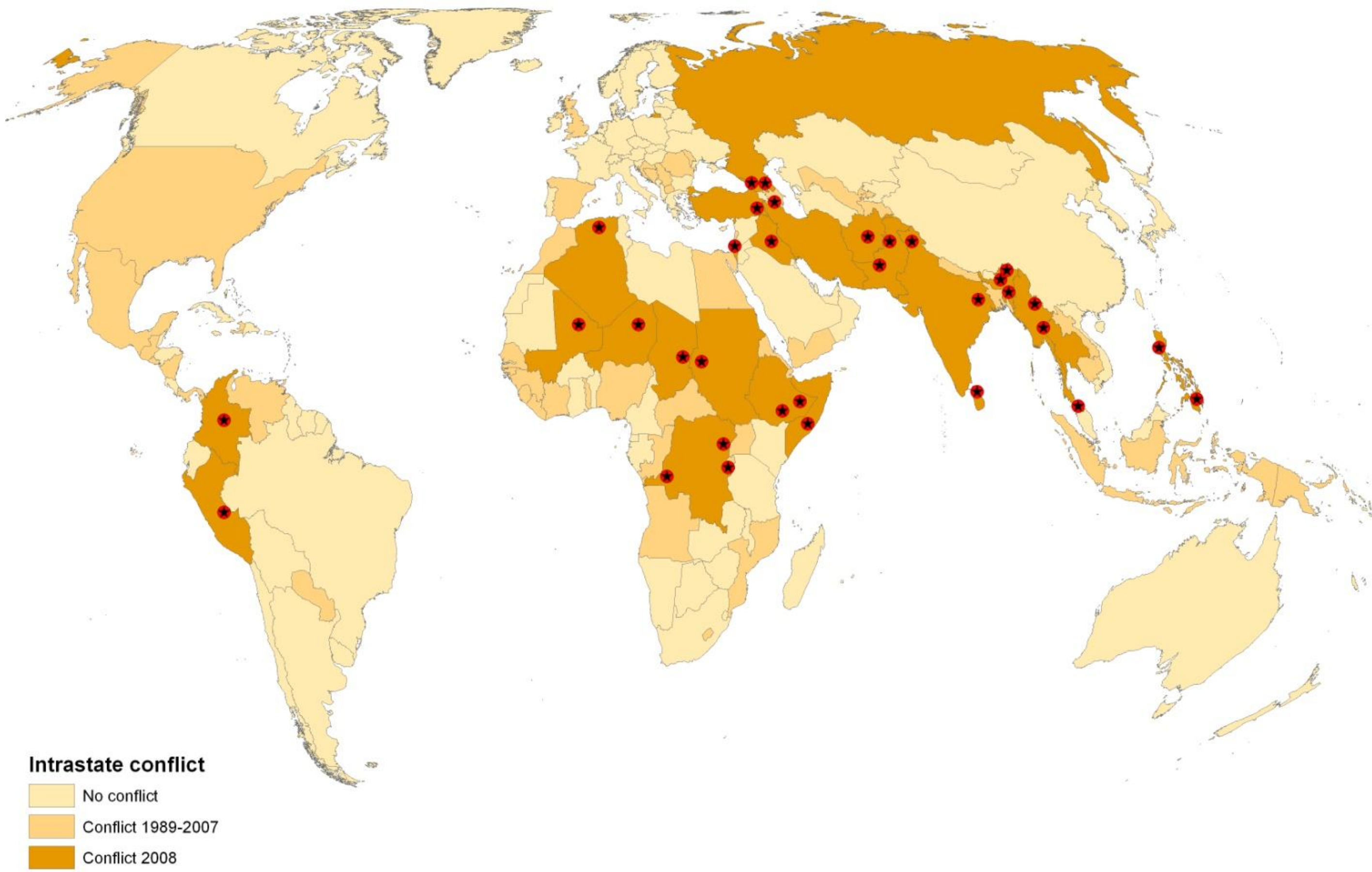
Hard to test for interactions of four factors …

From a policy perspective, easiest to reduce climate change or to change other factors in the interaction?

Vulnerable regions

- Africa is high on conflict, low on development, low on governance; includes two thirds of the 'bottom billion' countries. However, Africa is experiencing a decline in conflict, increasing economic growth, and improving governance
- East Asia had the most severe wars in the second half of the twentieth century; now largely peaceful
- Most battle deaths currently occur in Central and South Asia. Middle East also sees frequent conflict, but not currently very severe
- Empirical studies have focused on Africa (particular SSA) a) because it is more vulnerable b) because of low adaptive capacity

The distribution of armed conflict



Models

- Disagreements about security effects do not appear to depend on the choice of emissions scenarios
- No standard conflict model, but *Fearon & Laitin (2003) and *Collier & Hoeffler (2004) frequently used
- Endogeneity problems?
- *Ward, Greenhill & Bakke (2010): Standard conflict models do a poor job of predicting new conflicts
- If studies of historical data provide little evidence for a security effect, projection is less urgent

Uncertainty

- IPCC WG I : quantitative likelihood scale: Virtually certain = 99% probability of occurrence, etc.
- IPCC WG II: quantitative confidence scale: Very high confidence = 90% or higher chance of being correct
- IPCC WG III: qualitative level-of-understanding scale, high to low agreement on one axis, much to little evidence on the other
- IAC (2010) criticizes WG II for reporting high confidence in statements for which there was little evidence
- Peer-reviewed sources: relatively fewer in WG II than in WG I and even lower in WG III

Research priorities

- Look at interactions between climate change and political and economic factors
- Focus on countries with low adaptive capacity
- Look at a broader set of conflicts (one-sided, non-state, riots)
- Disaggregated studies of geo-referenced data
- Balance negative and positive effects (e.g. food)
- (possibly) Couple models of climate change to models of conflict

What if climate change has negligible impact on conflict?

Does it matter?

- For the credibility of climate change research – very much
- For mitigation – very little
- For adaption – possibly a lot

THANK YOU FOR YOUR ATTENTION

Migration Impacts of Climate Change

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Extended abstract for US EPA/DOE Workshop, "Research on Climate Change Impacts and Associated Economic Damages", January 27-28, 2011, Washington, D.C.

1. Briefly review existing studies of the impacts of climate change on intra- or inter-regional migration, with special attention to any existing quantitative estimates of the effects of changes in temperature, precipitation patterns, or sea level on migration patterns. Which regions are likely to be the most vulnerable to these impacts?

Scholars have long known that environmental conditions, including climatic variability and change, can and do influence human migration (Hugo 1996, Hunter 2005). Contemporary discussions of climate-related migration tend to be framed in terms of "environmental refugees" (a term coined by El-Hinnawi 1986), whereby people are involuntarily displaced in response to environmental conditions or events such as floods, droughts and so forth. A range of climatic events and conditions known from past experience to have stimulated distress migration are expected to increase in terms of frequency and severity in many reasons regions as a result of climate change (Solomon et al 2007, Parry et al 2007) (Table 1). However, distress migration represents only one end of a continuum of possible climate-migration outcomes, the other end being environmental amenity migrants who voluntarily seek better quality environmental conditions (e.g. "snowbird" migration of retirees from northern US to the sunbelt). Many other possibilities exist between the extremes of environmental refugee and amenity-seeker, and in many instances it may be difficult to distinguish environmental influences from political, economic, social, and similar cultural factors that influence migration behavior (Hunter 2005, Massey et al 2010, Suhrke 1994). For example, often overlooked in discussions of climate change-related migration is the potential effect on labor migration patterns, as the impacts of climate change reduce income possibilities in some regions or sectors and open up opportunities in new ones (e.g. economic development in the warming Arctic creating new development and labour migration there (McLeman and Hunter 2010)).

***Table 1** Expected impacts of anthropogenic climate change reported by IPCC and potential associations with future population displacements/migrations (adapted from McLeman 2011; McLeman & Hunter 2010)*

Expected biophysical changes (from Solomon et al 2007, Parry et al 2007)	**Regions at risk**	**Possible linkages to migration**
Decreased snow and sea ice cover	Arctic	Economic migrants arriving to take advantage of newly accessible resources
Higher average river runoff and water availability; more heavy precipitation events	High latitudes, some wet tropical areas	Flood-related displacements
Lower average river runoff and water availability; more	Mid- to low-latitudes and dry tropics; drought-prone	Water scarcity, drought, & decreased crop productivity leading to

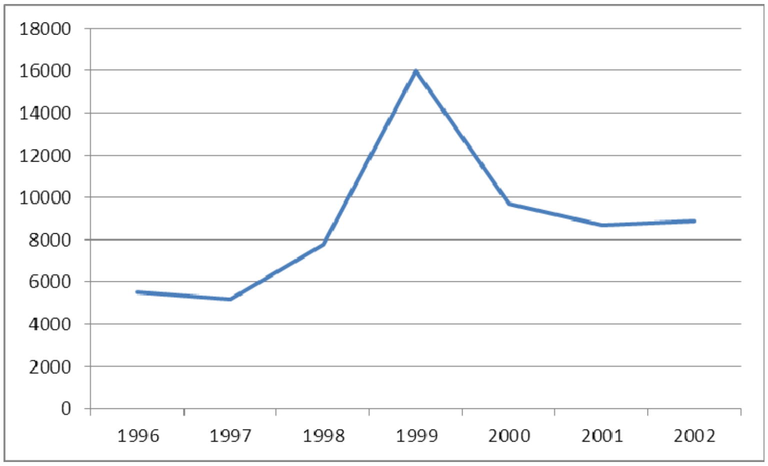
droughts in dryland areas	continental areas; areas receiving mountain snowmelt	migration, especially higher rates of rural-urban migration
Coastal erosion, extreme storms, sea level rise	Low-lying coastal regions, deltas small island states	Relocation of coastal settlements & infrastructure; salinization of water supplies

In the scientific community, human responses to the impacts of climate change are typically described in terms of vulnerability, which is in turn seen as being a function of the sensitivity of a given population, region or system to the types of climatic disturbances to which it may be exposed (often simply described as exposure), and the capacity of the population to adapt (Adger 2006, Parry et al 2007). Some types of settlement locations are more exposed to migration-inducing climate events than others, such as low-lying coastal areas and small islands; river valleys and deltas; dryland areas; regions where precipitation is highly seasonal; and, high latitudes and high altitudes (McLeman and Hunter 2010). In this context, migration is a process by which exposed individuals or households may adapt to climatic exposures (McLeman and Smit 2006, Perch-Nielsen et al 2008, Tacoli 2009, Bardsley and Hugo 2010). There are past examples of state-organized population relocations in response to climate-related events (e.g. resettlement after drought in East Africa in the 1980s and in Alberta/Saskatchewan, Canada in the 1930s (Ezra and Kiros 2001, Marchildon et al 2008)). However, most climate-related migration occurs as the result of autonomous responses by households and individuals, and consequently takes on many different shapes and forms. A single climate event may stimulate a variety of possible migration responses, as was seen following Hurricane Katrina (Fussell et al 2010).

The greatest amount of climate-related migration presently occurs at intra-national or intra-regional scales, and this is expected to continue to be the case in coming decades (Adamo and Izazola 2010, Massey et al 2010, Nelson 2010). In developing regions, where economic systems and livelihoods are closely tied to agriculture and natural resources, extreme climatic events and conditions are expected to accelerate already growing levels of rural-to-urban migration (Hunter 2005, McLeman and Hunter 2010). People at the lowest end of the socio-economic spectrum – particularly landless laborers and tenant farmers – are the most mobile and most easily displaced (Massey et al 2010). Landowners, business operators and others at the upper end of the socioeconomic spectrum will also experience economic hardship, but are more likely to resist migration because their household capital is tied to land and other assets that are not transportable (McLeman and Smit 2006). Cyclical intra-regional migration in response to seasonal variability in precipitation and periodic droughts has already long been practiced in Sudano-Sahelian Africa and rural South Asia and this is expected to continue and potentially grow (Deshingkar & Start 2003, Hampshire 2002, Mortimore and Adams 2001, Nyong et al 2006).

International movements of people are also expected to increase in response to climate change, particularly along established migration routes and making use of social networks and transnational communities (McLeman and Hunter 2010). This belief is supported by evidence from recent climate-related migration movements, including examples involving the US. For example, Feng et al (2010) have observed that migration from Mexico to the US surges when drought conditions exist in rural Mexico. Hurricane Mitch was followed by a pulse of Honduran migration into neighbouring countries and to the US (Figure 1). Popular media have suggested that anthropogenic climate change has already begun causing migration from small Pacific islands to Australia and New Zealand, but there currently exists no peer-reviewed research to support this suggestion (Mortreux and Barnett 2009). Case study findings from the EU/UNU-led EACHFOR project on climate and migration,[1] which was completed in 2009, may provide additional insights into international migration prospects under future climate change, but the results have yet to appear in scholarly journals.

Figure 1*: Apprehensions of improperly documented Honduran migrants along southern US border pre- and post-Hurricane Mitch (Oct-Nov 1998)*



Data source: US Department of Homeland Security Office of Immigration Statistics

While there is increasing agreement on the regions and populations most at risk of experiencing climate change-related migration, quantitative forecasts are few and vary considerably. The most widely-cited prediction is one made by British ecologist Norman Myers, who suggested there may be 200 million environmental refugees worldwide by mid- to late century, to be displaced by a variety of environmental changes including climate change and sea level rise (Myers 2002). Similar predictions have been made by CARE International (2009), while the relief organization Christian Aid (2007) suggested as many as one billion people could be displaced from their homes by mid-century from the combination of anthropogenic climate change and other global environmental changes. McGranahan et al (2007) maintain a Low Elevation Coastal Zone database and have used it to estimate that 10% of the world's population (15% of the global urban population) lives within ten metres of sea level, and is potentially exposed to the impacts by sea level rise.

2. Briefly review the models and data used to estimate these impacts. What factors are most important to capture in such models when thinking about the migration impacts of climate change over a long time frame?

<u>Data for estimating climate change-related migration</u>

Lack of reliable data constitutes a severe and ongoing impediment to reliable forecasting of climate change-related population movements. Data on global-scale population movements are generally coarse in nature, and those pertaining to environmental stimuli are particularly unavailable (Brown 2008). The Population Division of the UN Department of Economic and Social Affairs estimates the

[1] http://www.each-for.eu

world's current annual migrant population at slightly more than 200 million (UN DESA 2010); it is not indicated what proportion migrate for environmental reasons. The United Nations High Commission for Refugees (UNHCR) reported an estimated 10.4 million refugees worldwide, and another 15.6 million involuntarily displaced within their own borders at the end of 2009 (the last year for which figures were reported at time of writing)(UNHCR 2010). Because environmental stimuli do not qualify as valid reasons for seeking refugee protection, these statistics do not capture people who are involuntarily displaced for climate-related reasons, and the UNHCR offers no estimates for such categories of people. The UN's International Strategy for Disaster Reduction and the Centre for Research on the Epidemiology of Disasters provide annual estimates of the number of people affected by natural disasters affecting 100 people or more per event, broken down by type of disaster (of which some, but not all, are climatic in nature). These provide crude proxy figures from which to make estimates of involuntary climate change-related migration. It is important to note, however, that not all of those affected by disasters become migrants; many resume their former place of residence as soon as it is safe to do so. Furthermore, many environmentally induced displacements and movements of people are driven by small-scale, frequent or repetitive events that may not show up in disaster reporting (Gutmann and Field 2010).

Modeling of climate change-related migration

Modeling of climate change-related migration is still an emergent area of research. Much of the current work to date can be loosely described as *spatial vulnerability modeling,* having been influenced by techniques developed in natural hazards vulnerability research (e.g. Clark et al 1998, Cutter et al 2000, Wilhelmi and Wilhite 2002). These types of models identify areas or populations vulnerable to particular impacts of climate change by using geographic information systems (GIS) to combine modeled climate data from general circulation models (GCMs) or regional climate models (RCMs) with various types of population, agro-economic and/or resource data (e.g., Byravan et al 2010, Mcgranahan et al 2007, O'Brien et al 2004, Polsky 2004, Vorosmarty et al 2000). From these, assumptions are then made about the potential for population displacement and migration, as was done for example in the CARE International 2009 report cited previously. These models can be extended to identify potential sites of climate change-related conflicts (which would have feedback effects on migration), as is presently being done at the University of Texas-Austin to identify sites of potential climate change-related conflict in Africa[2] and at Oregon State to identify potential sites of freshwater conflict.[3]

Migration estimates based on spatial models make an assumption that an increase in exposure to a particular climatic stress stimulates a corresponding increase in migration (Piguet 2010). This assumption is inherently unreliable, because climate-migration rarely unfolds in simple stimulus-response fashion, but is instead heavily moderated by intervening economic, social and cultural variables (McLeman and Smit 2006, Massey et al 2010). For example, McLeman et al (2010) combined regional climate data and census information to create a GIS model of drought-related population change known to have occurred in western Canada in the 1930s. While the model successfully captured spatial associations between population change and drought for that particular decade at regional scales, the model has not yet been able to reproduce drought migration patterns in subsequent decades for the same region. This is because institutional and economic structures changed substantially over subsequent decades, requiring incorporation of additional data and modification of the underlying

[2] http://ccaps.strausscenter.org/about

[3] http://www.transboundarywaters.orst.edu/research/case_studies/index.html

assumptions of causality built into the model. Enhancing the predictive capacity of spatial vulnerability models and "ground-truthing" them requires complementary qualitative field research to identify the factors and interactions (macro-level and context-specific) that transform vulnerability to migration.

Identification of vulnerable areas and populations that might experience climate-related migration is not, however, the same as being able to quantify the number of likely migrants. A second type of modeling that may hold promise for climate change migration research is *hazard analysis modeling*, which focuses on capturing the migration behavior of individuals or particular population groups (Barber et al 2000). Somewhat confusingly, the use of the term "hazard" with respect to this modeling method does not relate to environmental hazard stimuli but is simply a generic term denoting any potential lifecourse event (e.g. having a child, changing jobs, migrating, etc) that is contingent upon other variables, one of which could conceivably be changes in climatic or environmental conditions. In general migration research, this type of modeling has been used to understand the timing of migration events in response to particular stimuli (i.e. time-hazard modeling (e.g. Odland and Shumway 1993)) and in identifying potential migration stimuli operating across multiple scales (i.e. multi-level hazard modeling (e.g. Massey & Espinosa 1997)). The types and quantity of data necessary to apply this type of modelling to climate change migration are not widely available at present, although it has been applied in studies of other types of environmental migration, such as the impacts of land degradation on rural migration in Nepal (e.g. Massey et al 2010). A research group at the University of Sussex, England, is currently developing a multi-level hazard method described as *agent-based modelling* to develop forecasts of climate change migration, a method which derives multiple hypotheses about migrant behaviour from known migration data to create computer simulations (Kniveton et al 2008). The researchers have been attempting to apply the method to drought migration in Burkina Faso; results have yet to appear in scientific literature.

3. Characterize the uncertainty / robustness / level of confidence in these estimates, on average globally and by region.

There is a great deal of convergence in the research in terms of global and regional scale identification of areas and populations potentially at risk of experiencing population displacements and distress migration due to climate change. This situation will likely improve in the short run due to improvements in the availability of regional climate model data. Reliable local and sub-regional identification of potential climate change-related distress migration hotspots is not yet widely available and requires more research.

Existing estimates of future climate change migration numbers are inherently speculative and often anecdotal, and are consequently viewed with considerable scepticism by many scholars (Massey et al 2010, McLeman and Hunter 2010). This is to be expected given the limited availability and quality of regional climatic and population data and our weak understanding of the process linkages between climatic stimulus, migration outcome and intervening socio-economic and cultural processes. Most climate change-related migration is expected to occur within regions and borders, and is likely to include not only distress migrants but large numbers of voluntary migrants as well.

No global monitoring program presently exists for capturing environmentally-related population movements across international borders or internal movements. For particular regions and sub-regions, researchers have developed detailed datasets that include linked environmental information and population and migration data over particular time periods, with Burkina Faso, Nepal, and Amazonian Brazil being just some examples (Kniveton et al 2008, Massey et al 2010, Parry et al 2010). These disparate datasets are not necessarily linkable to create larger scale models, may not cover similar time periods and may not be maintained on an ongoing basis. In summary, reliable forecasts of climate change migration numbers (as opposed to populations at risk) are many years off.

4. What are the most important gaps or uncertainties in our knowledge regarding the migration impacts of climate change? What research in this area would be most useful in the near term?

One important area for additional research is in enhancing our understanding of the underlying connections between climatic stimuli, intervening socio-economic factors and migration decision-making outcomes. Evidence from known climate-related migration events shows that migration responses to climatic stimuli are highly variable within and across populations (McLeman and Hunter 2010). Not all households exposed to a given climate event adapt through migration, and not all those who might migrate do so (McLeman and Smit 2006). Understanding the underlying forces responsible for differential migration responses is important for translating spatial vulnerability models into reliable forecasting models. Massey et al (2010) have suggested that migrants may act on the perception of an impending environmental risk rather than waiting for the actual occurrence of the environmental risk itself; if so, this is an area that is greatly understudied. Social networks and social capital are also believed to be significant influences on climate-related migration and therefore warrant further research attention (Gilbert and McLeman 2010, Massey et al 2010). The potential effects of climate change on intraregional and international labor migration patterns is virtually unexplored and warrants close attention, particularly given recent empirical findings regarding the influence of climatic conditions on labor migration within the Himalayan region and between Mexico and the US (Banerjee 2010, Feng et al 2010).

A second area of uncertainty, and one where US and international policymakers have an opportunity to play an important role, is in the creation of a protocol and mechanisms for generating global statistics on internal and international migration undertaken for environmental reasons. As indicated above, existing datasets relating to refugees and disaster displacements provide only rough and unreliable proxies for measuring the effects of climate and other environmental events and conditions on migration. A global environmental migration monitoring initiative would in principle be a relatively straightforward undertaking, requiring a simple protocol that might be enacted through an existing international agreement such as the UN Framework Convention on Climate Change. A range of existing international institutions, including various UN agencies and the International Organization for Migration, have the potential wherewithal for collecting and maintaining such statistics and would require modest incremental resources to do so. Such an initiative would be a particularly useful step forward in transforming discussion of climate change migration from informed speculation to evidence-based policy-planning.

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Migration Impacts of Climate Change

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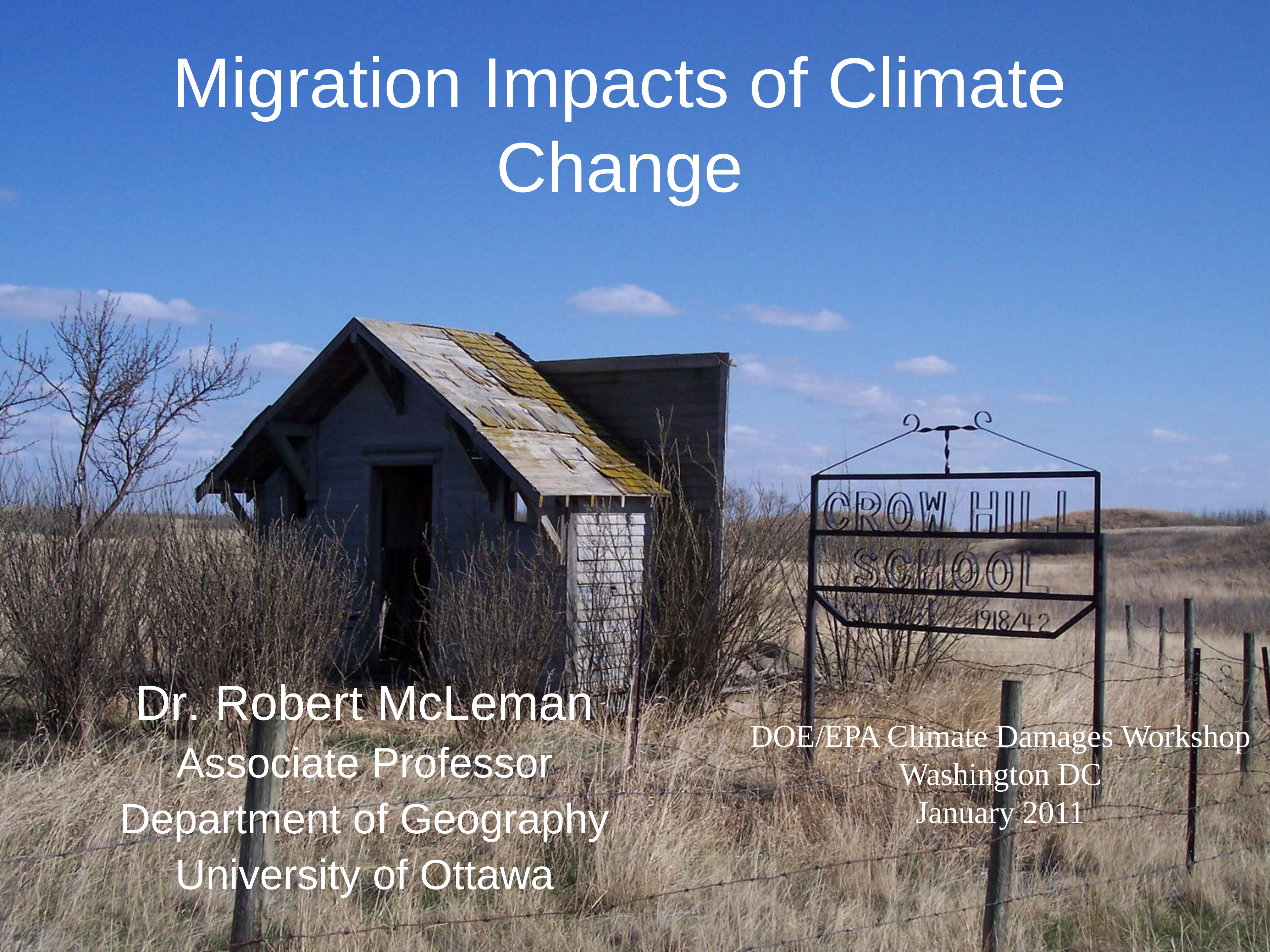
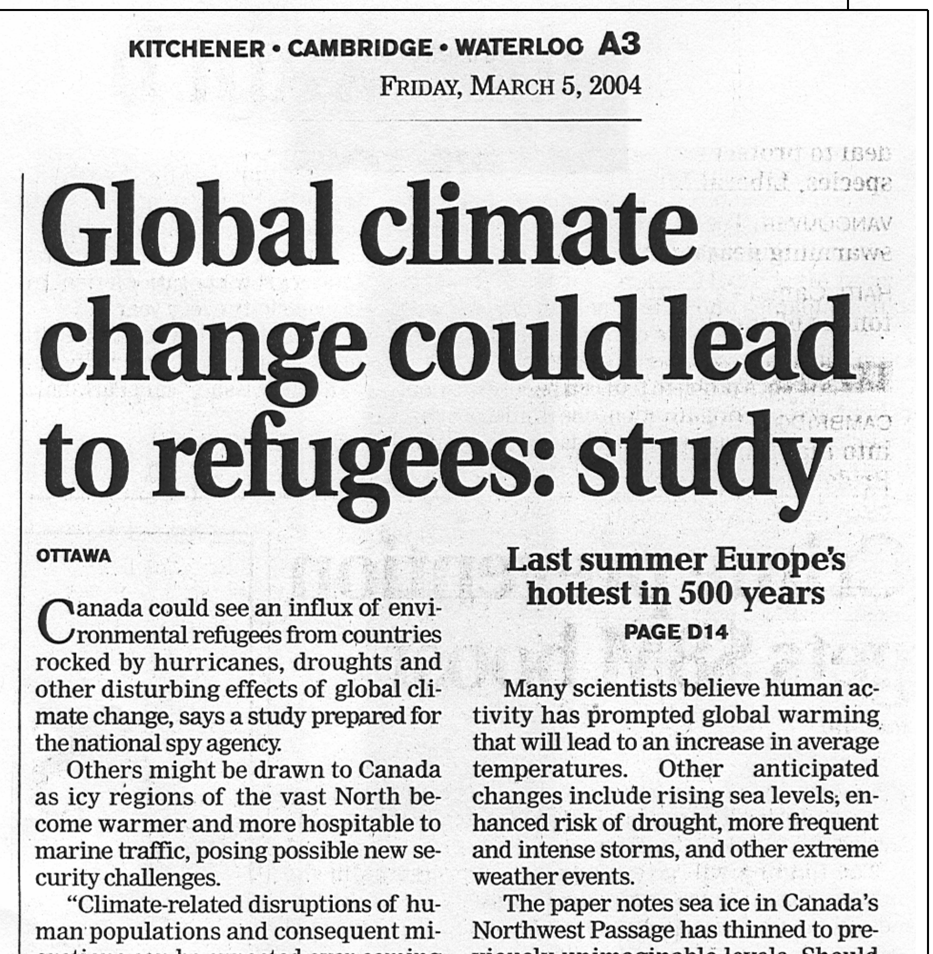
DOE/EPA Climate Damages Workshop
Washington DC
January 2011



Questions

- What regions most vulnerable?
- What models/data are available?
- How confident are we in these?
- Gaps & opportunities

Predictions of a coming exodus



KITCHENER • CAMBRIDGE • WATERLOO A3
FRIDAY, MARCH 5, 2004

Global climate change could lead to refugees: study

OTTAWA

Canada could see an influx of environmental refugees from countries rocked by hurricanes, droughts and other disturbing effects of global climate change, says a study prepared for the national spy agency.

Others might be drawn to Canada as icy regions of the vast North become warmer and more hospitable to marine traffic, posing possible new security challenges.

"Climate-related disruptions of human populations and consequent mi-

Last summer Europe's hottest in 500 years
PAGE D14

Many scientists believe human activity has prompted global warming that will lead to an increase in average temperatures. Other anticipated changes include rising sea levels, enhanced risk of drought, more frequent and intense storms, and other extreme weather events.

The paper notes sea ice in Canada's Northwest Passage has thinned to pre-

The New York Times
ON THE WEB

Before the Flood

By SUJATHA BYRAVAN and SUDHIR CHELLA RAJAN
Published: May 9, 2005

Cambridge, Mass. —. One of the paradoxes of global warming is that developing countries, which were not responsible for most of the greenhouse gas emissions that are changing the climate and did not reap the benefits of industrialization, will bear the brunt of the consequences. **One of these consequences will be rising seas, which in turn will generate a surge of "climate exiles" who have been**

Media identification of the first climate change refugees

Shishmaref, Alaska

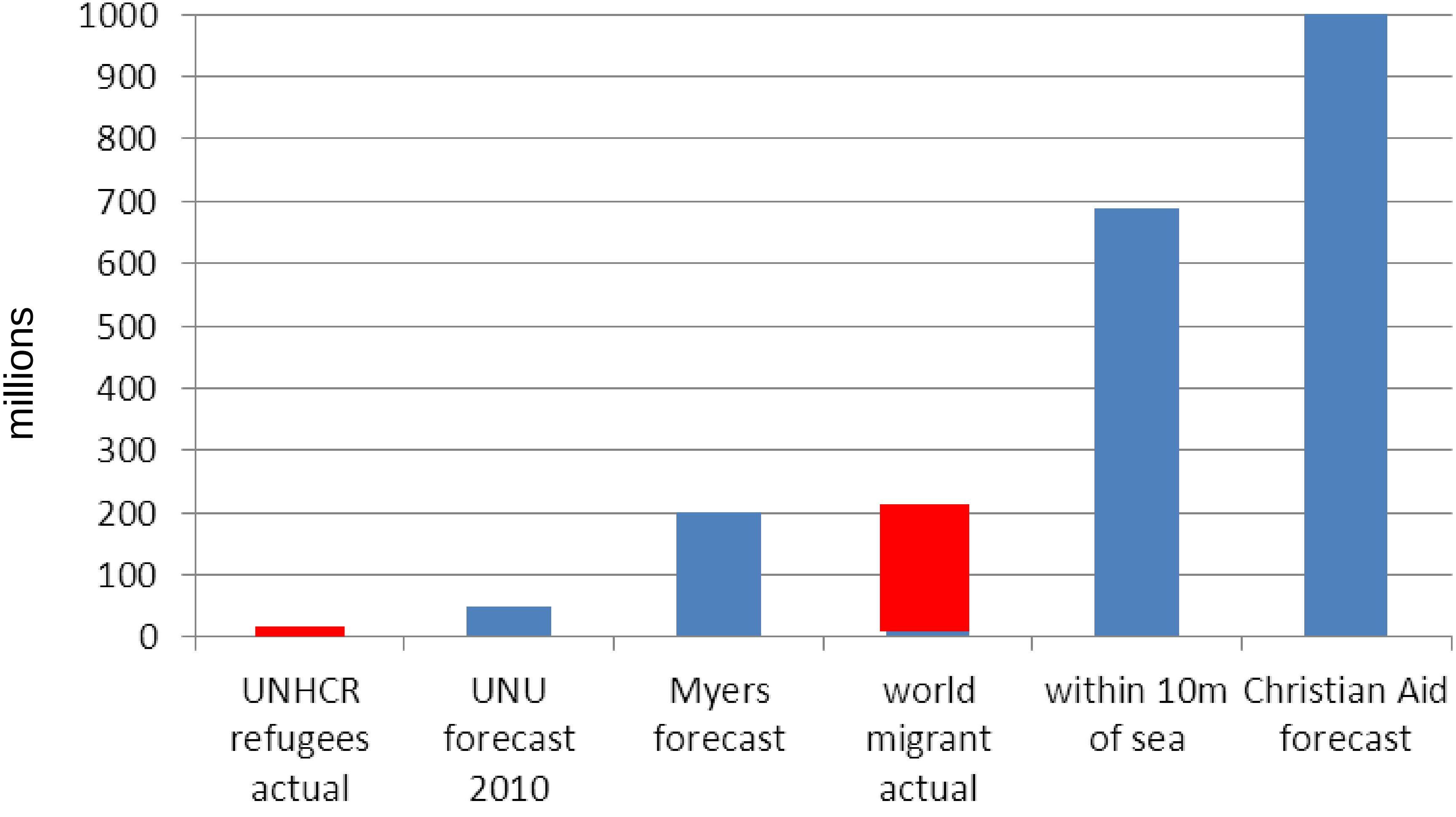
Cataret Islands

Lake Chad region

Predictions of future environmental refugees

- Up to 1 billion by 2050 (Christian Aid)
- 200 million by 2050 or 2100 (Norman Myers, CARE International press release)
- 50 million by 2010 (UNU 2005 press release)
- 10% of world population lives within 10m of sea level (Mcgranahan et al 2007)

Context



millions
1000
900
800
700
600
500
400
300
200
100
0
UNHCR refugees actual
UNU forecast 2010
Myers forecast
world migrant actual
within 10m of sea
Christian Aid forecast

Existing forecasts of climate change migration

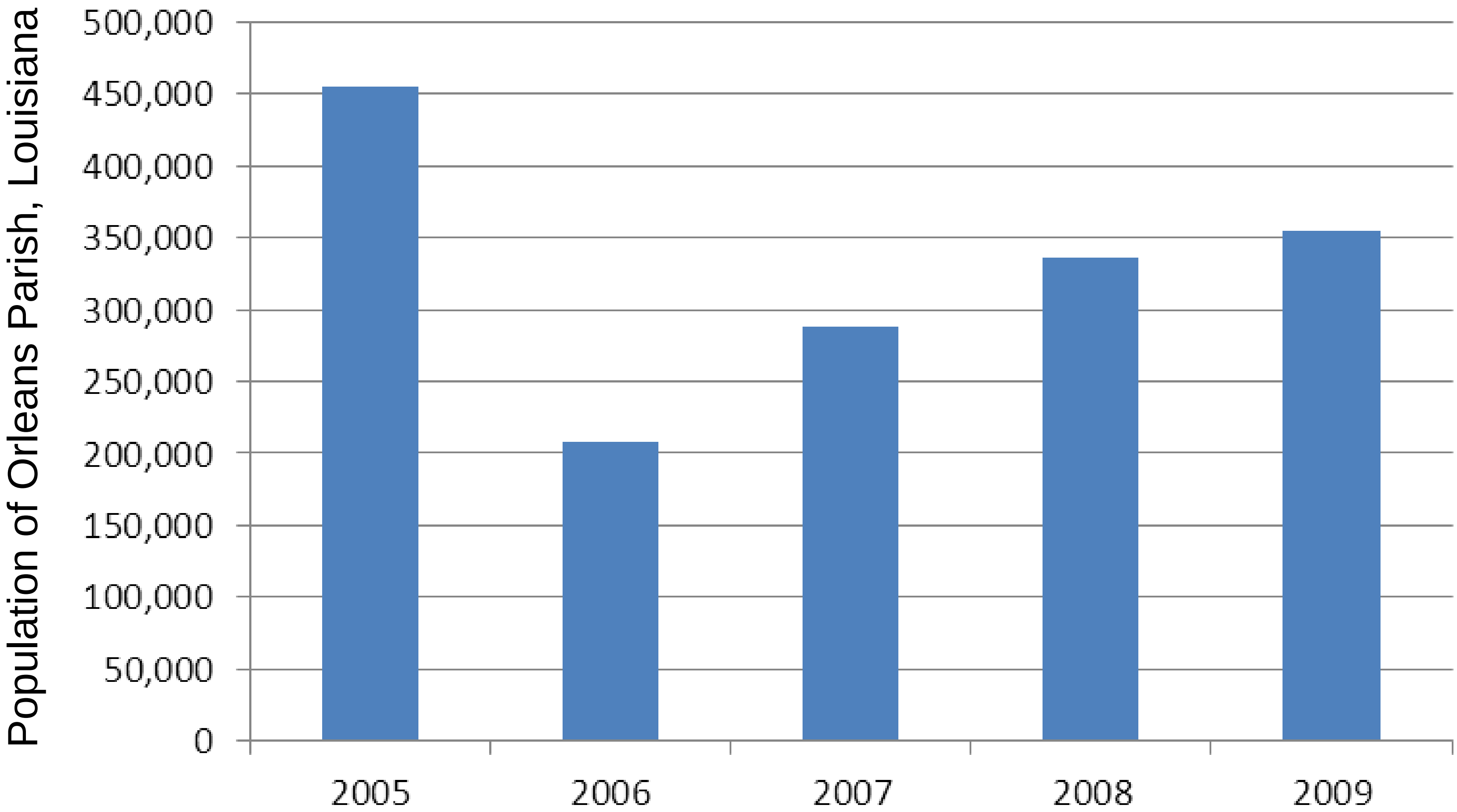
- Identify areas/populations exposed to negative CC impacts
- Exposure ≠ migration
- Climate-migration not simple stimulus-response
- Intervening socio-economic, cultural & institutional factors

Climatic stimuli known to be associated with migration

- Sudden onset events (e.g. hurricanes, tropical storms, extreme rainfall events)
- Persistent conditions (e.g. drought, changes in monsoons)
- Climate change expected to exacerbate existing stimuli, create new ones (e.g. sea levels, Arctic ice)

Hurricane Katrina

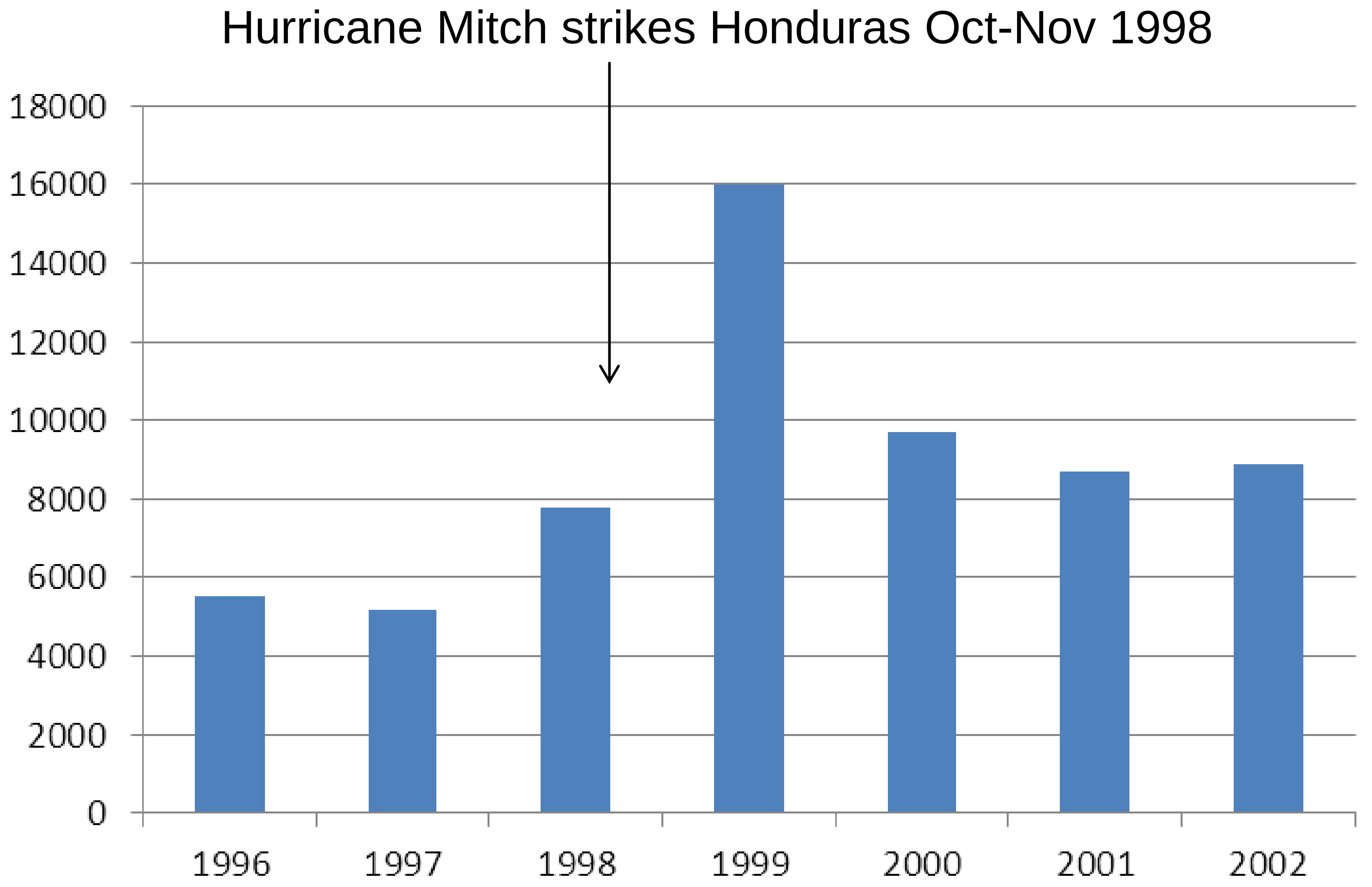
New Orleans population post-Katrina



Data source: US Census bureau
http://www.census.gov/popest/counties/CO-EST2009-01.html


Hurricane Mitch, 1998
NASA image

Undocumented Hondurans arrested at US-Mexico border



Drought & migration

- Feng et al (2010) find that a 10% decrease in agricultural production in Mexico due to drought is associated with a 2% rise in Mexican migration to US

Feng SF, Krueger AB, Oppenheimer M. (2010) Linkages among climate change, crop yields and Mexico–US cross-border migration. *Proceedings of the National Academy of Science*. 107(32):14257-14262.

Where will climate change generate migration stimuli?

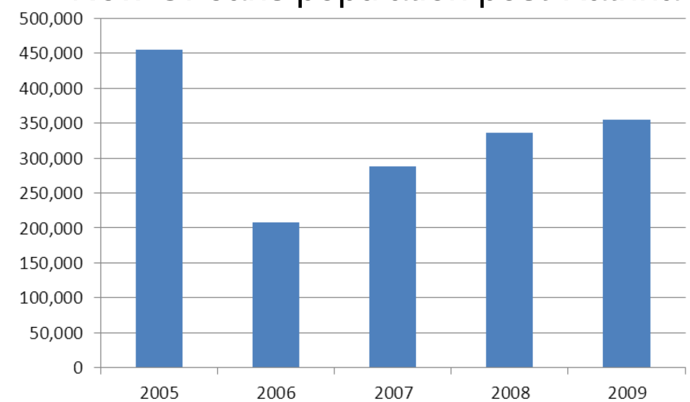
- Arctic (permafrost, sea & land ice melt)
- High latitudes, wet tropics (heavy precipitation events, floods)
- Mid- to low-latitudes, dry tropics (drought, water scarcity)
- Coastal plains, deltas, small islands (erosion, storm surges, salinization)

IPCC 2007 distilled by McLeman & Hunter 2010

Differential outcomes

- Climate events, conditions don't always stimulate migration
- Multiple migration outcomes can be generated by single climate event
- Why? What distinguishes migrants from non-migrants?

New Orleans population post-Katrina



Vulnerability (V)

- Potential to experience loss or harm

$$V = f(E,S,A)$$

E = exposure (i.e. climatic stimulus)

S = sensitivity of the exposed system

A = adaptive capacity

$V = f(E,S,A)$

Adaptive capacity

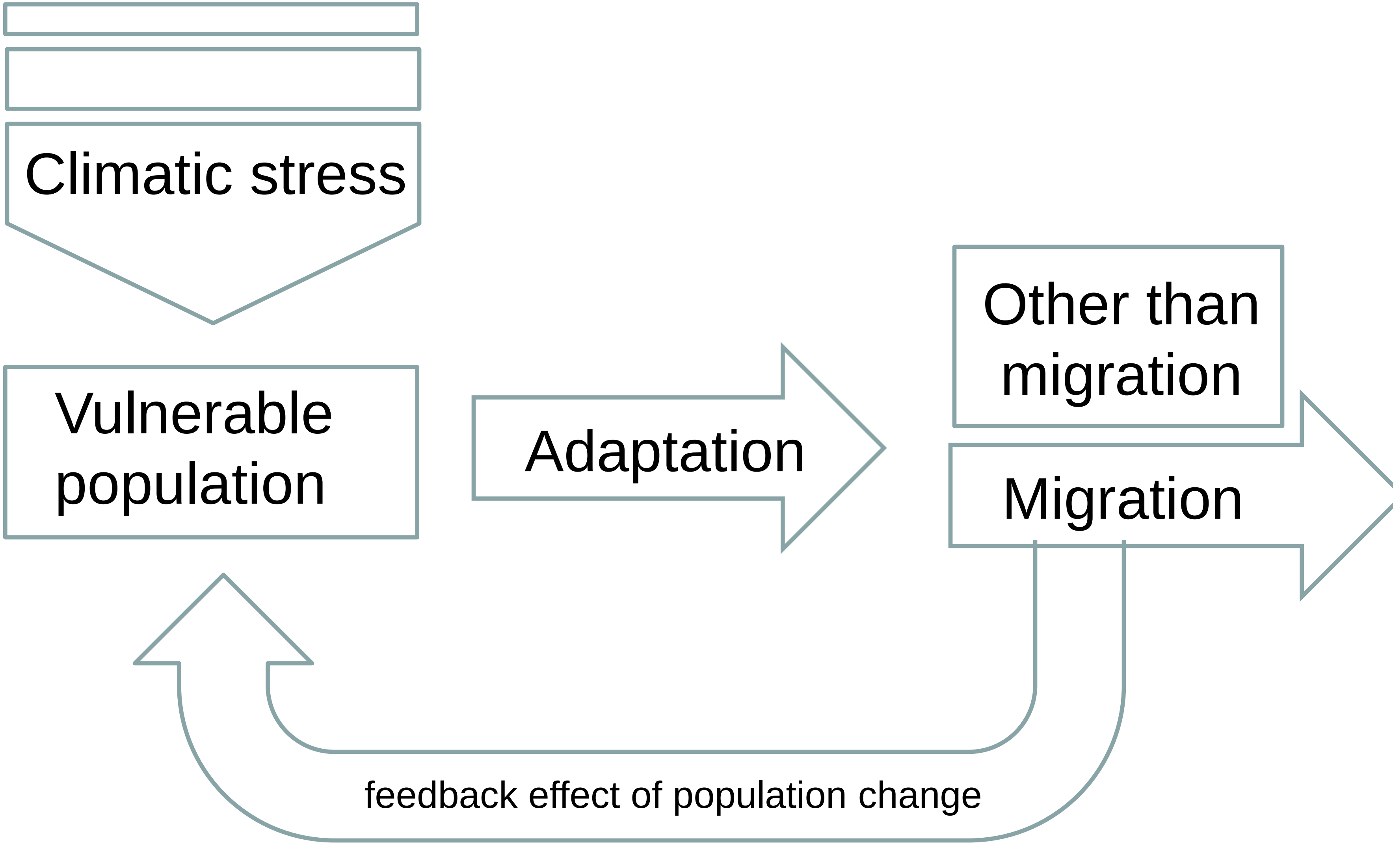
- Options for adapting to drought not the same in rural Nigeria as in rural Saskatchewan

Northern Nigeria, 2005

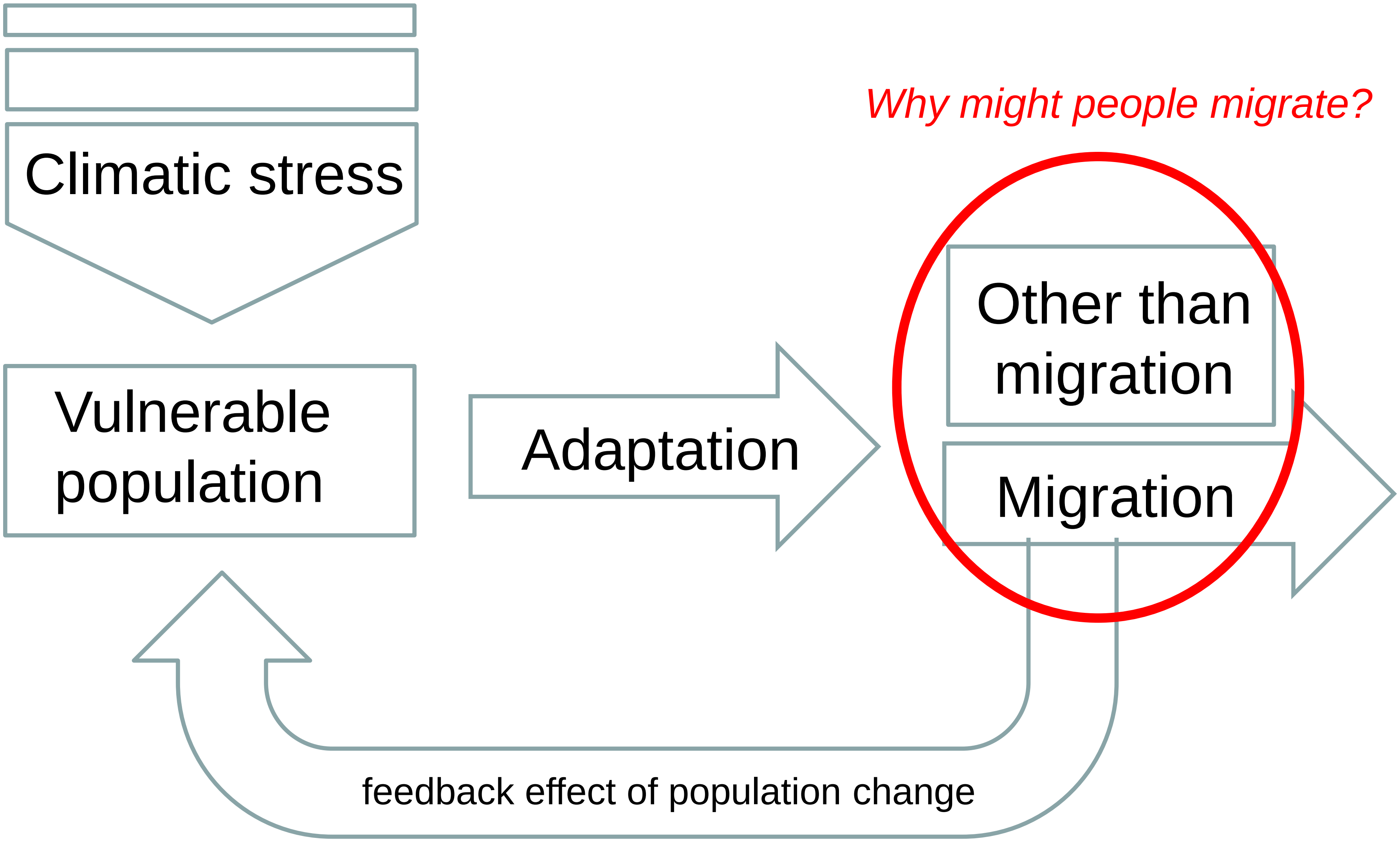
Saskatchewan 2002

Migration as adaptation

- Migration is one of a range of potential adaptive responses to environmental stress
- Is presently used in many parts of world
- Is typically initiated at the household level
- Is not available to everyone
- Is not always used by all who might do so
- In worst cases, could be the only adaptation



Simplified from McLeman R, Smit B. (2006) Migration as an Adaptation to Climate Change. *Climatic Change*. 76(1-2):31-53.



Simplified from McLeman R, Smit B. (2006) Migration as an Adaptation to Climate Change. *Climatic Change*. 76(1-2):31-53.

What else motivates people to migrate?

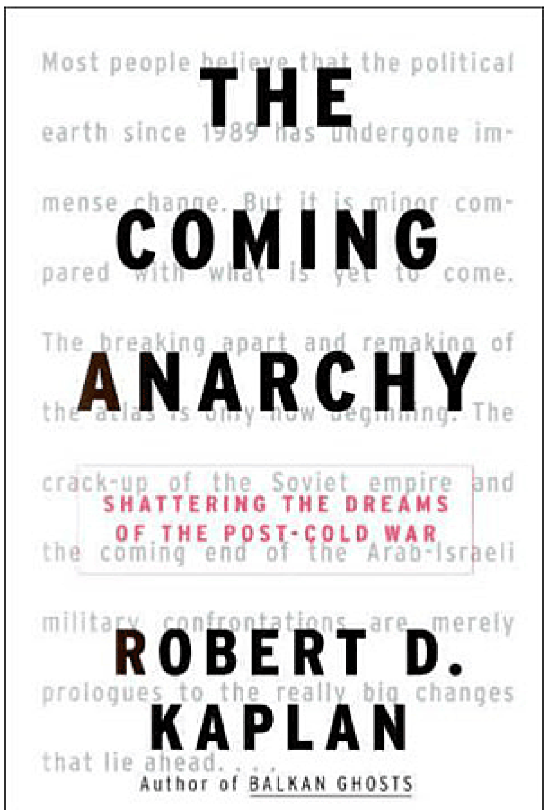
- Opportunity/benefit seeking (economic, public services)
- Household risk diversification
- Macro-scale systems
- Cultural norms
- Lifestyle
- Bright lights-big city
- Love
- Persecution, fear of violence

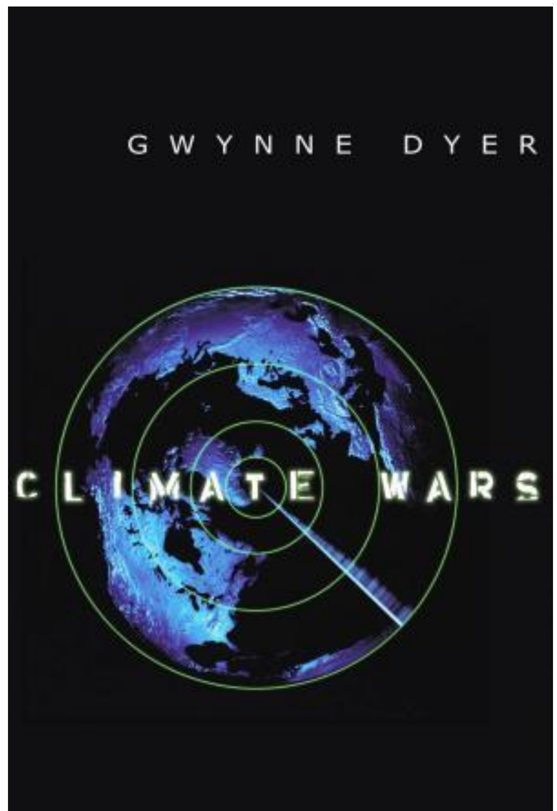
What else motivates people to migrate?

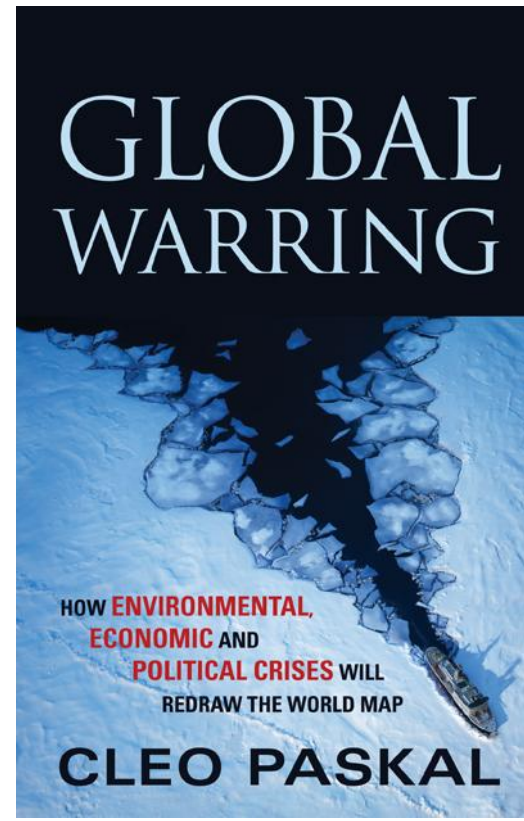
- Opportunity/benefit seeking (economic, public services)
- Household risk diversification
- Macro-scale systems
- Cultural norms
- Lifestyle
- Bright lights-big city
- Love
- Persecution, fear of violence

Climate may influence/interact with any of these (except maybe love)

What do we tend to focus on?

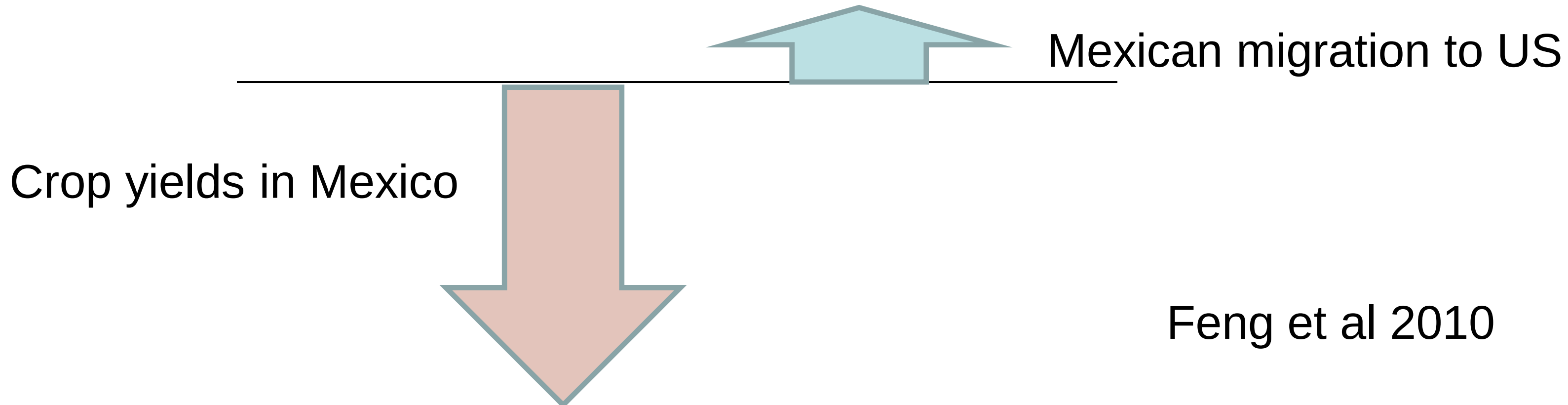






But most observed climate-related migration…

- Is not conflict-related
- Is internal/intra-regional
- When international, follows established routes, transnational communities
- Is shaped by other motivations as well



Feng et al 2010

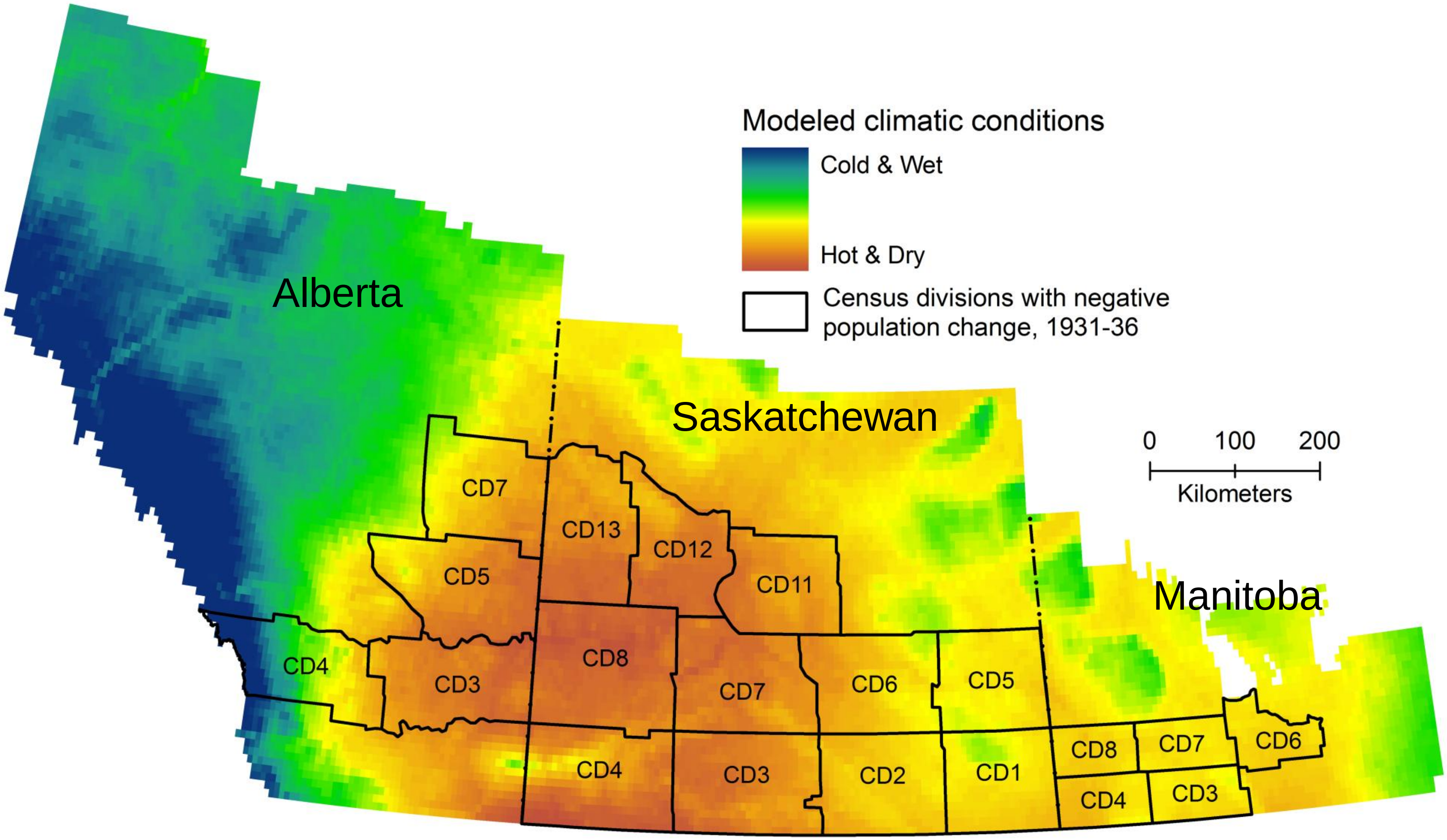
Climate-migration models

Historical climate-migration modeling

- Use known climatic data and known population change data from past events
- Generates learning analogues
- Can be ground-truthed

Canadian drought refugees, 1930s

Drought & rural population loss,1931-36, Canadian prairies



McLeman et al. (2010). GIS-based modeling of drought and historical population change on the Canadian Prairies. *Journal of Historical Geography, 36*, 43-56.

What distinguished migrants from non-migrants?

Qualitative research

Who migrates?

More likely to migrate:

- Young, healthy, skilled, educated
- Middle class
- Uncertain land tenure
- Family ties elsewhere

Less likely to migrate:

- Wealthier classes, landowners (especially good land), owners of fixed assets
- Those with strong local social networks

- Poor, destitute
- Elderly, infirm, broken families

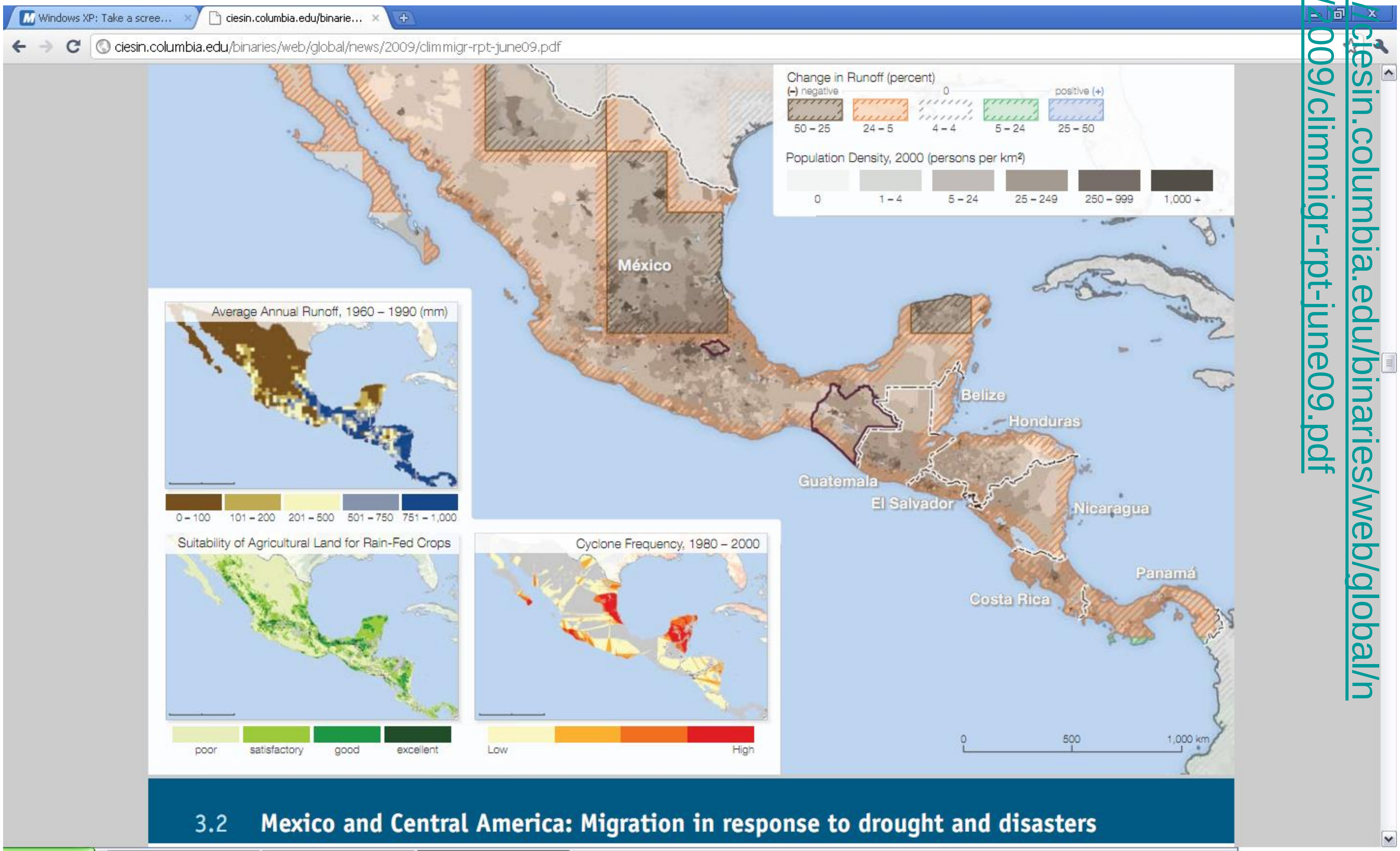
Other types of modeling

Spatial vulnerability models

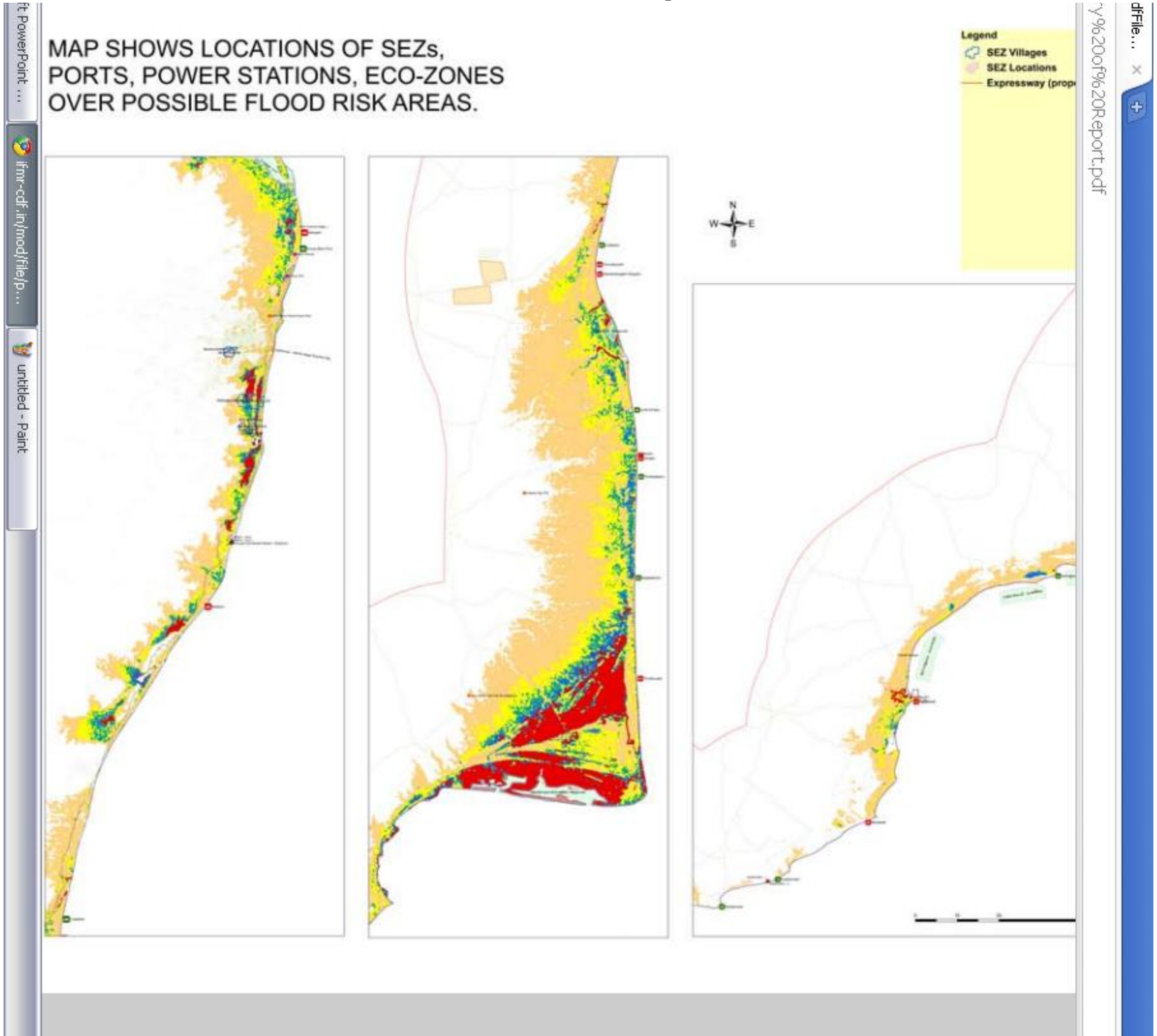
- GIS-based modeling to identify places/ populations at future risk (potential hotspots)
- Are silent on likelihood of migration outcomes

CIESIN models for "In Search of Shelter" report

http://ciesin.columbia.edu/binaries/web/global/news/2009/climmigr-rpt-june09.pdf



Byravan et al models of sea level rise & coastal settlement, Tamil Nadu



http://ifmr-cdf.in/mod/file/pdfFiles/Summary%20of%20Report.pdf

Other types of modeling

- Multi-level hazard analysis models
- Does not refer to natural hazards, but is statistical tool to isolate the relative effect of particular variables on migration outcomes
- Used by Massey, Axinn, others to estimate determinants of Mexico-US migration, environmental drivers of migration in rural Nepal

Massey, D. S., Axinn, W. G., & Ghimire, D. J. (2010). Environmental change and out-migration: evidence from Nepal. *Population and Environment*, 32(2-3), 109-136.
Massey, D. S., & Espinosa, K. E. (1997). What's driving Mexico-US migration? A theoretical, empirical and policy analysis. *American Journal of Sociology*, 102(4), 939-999.

Other types of modeling

- Multi-stage regression model of known & estimated migration + crop yield change
- Then combined with crop simulation models for forecasting
- E.g. estimating potential Mexico-US migration (Feng et al 2010)

Feng SF, Krueger AB, Oppenheimer M. Linkages among climate change, crop yields and Mexico–US cross-border migration. *Proceedings of the National Academy of Science*. 2010;107(32):14257-14262.

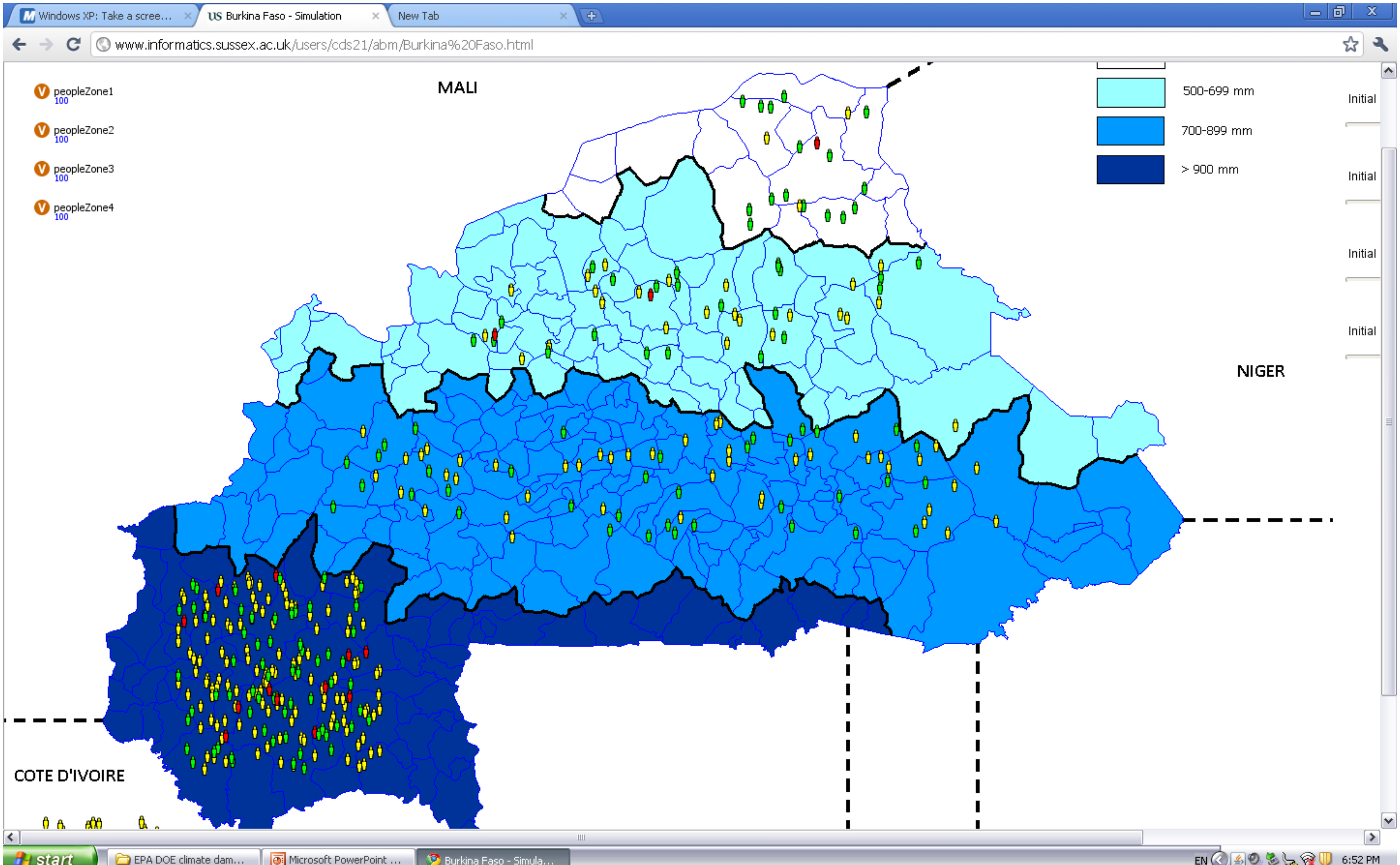
Other types of modeling

- Agent-based modeling
- Simulation modeling to attempt to replicate & then predict interactions (in this case between climatic stimuli & migration outcomes)
- Being used by group at U of Sussex to model drought migration in Burkina Faso

Kniveton, D. R., Schmidt-Verkerk, K., Smith, C., & Black, R. (2008). Climate change and migration: improving methodologies to estimate flows. Geneva: International Organization for Migration.

Agent-based model by Smith for Burkina Faso migration

http://www.informatics.sussex.ac.uk/users/cds21/abm/



Challenges & opportunities

Challenges

- Data availability, reliability
- No single global database
- Fragmented data for various regions, time periods
- Even where you have census data for population change/migration, reasons for migration often missing
- Proxy data: disaster displacements (not the best)

Challenges

- Understanding system linkages
- Role of intervening variables (e.g. perception, social networks, labour migration pressures/opportunities…)
- Uncertainty about future frequency/severity of migration-assocated climatic stimuli

Opportunities

- To develop monitoring & data collection protocols
- To enhance empirical research into environment & migration linkages
- To develop & improve migration models as climate change models improve

Thanks! Merci!

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Final Panel Discussion: Food for Thought

Anthony C. Janetos, Director

Joint Global Change Research Institute

28 January 2010

Our Charge

- How do we take all we have learned in the past two days to improve reduced-form integrated assessment models (IAMs)?
- In which sectors or categories has research on physical impacts of climate change or methods for valuing the associated damages developed beyond what is currently represented in reduced-form IAMs? Which of these can most readily be incorporated into modified versions of existing IAMs? How could one approach modeling the interactions across individual impact sectors?
- From the perspective of your discipline/area of expertise (e.g. economist, scientist, IAM modeler), what are the most important gaps or uncertainties in our knowledge regarding the impacts of climate change and associated economic damages? What research would be most useful in the near vs. long term?

The Short Version of My Answers

- How do we take all we have learned in the past two days to improve reduced-form integrated assessment models (IAMs)?
- Many different possibilities, but not clear to me that it's always a good idea.
- In which sectors or categories has research on physical impacts of climate change or methods for valuing the associated damages developed beyond what is currently represented in reduced-form IAMs?
- Pretty much all of them with respect to physical impacts. Methods for economic valuation appear at first glance not to have advanced nearly as much. Methods for incorporating valuation and physical impacts into reduced form models are increasingly sophisticated, but we need to be careful about what either the data or the models are capable of doing.
- Which of these can most readily be incorporated into modified versions of existing IAMs?
- Relatively few, without some fairly extensive thought given to thresholds, non-linear behavior, and process-level understanding.
- How could one approach modeling the interactions across individual impact sectors?
- Need explicit representation of the sectors and both the economic and physical factors (e.g. competition for water and land) that connect them.
- From the perspective of your discipline/area of expertise (e.g. economist, scientist, IAM modeler), what are the most important gaps or uncertainties in our knowledge regarding the impacts of climate change and associated economic damages? What research would be most useful in the near vs. long term?
- See below

Background

- The challenge to all the modelers in the workshop has essentially been framed in a “social cost of carbon” framework
- Assumes that we have good central estimates of a large number of parameters, both physical and economic, but is this reasonable?
- Many reasons in particular cases that we should be humble about our ability to generate really good estimates, so I will highlight only a few…

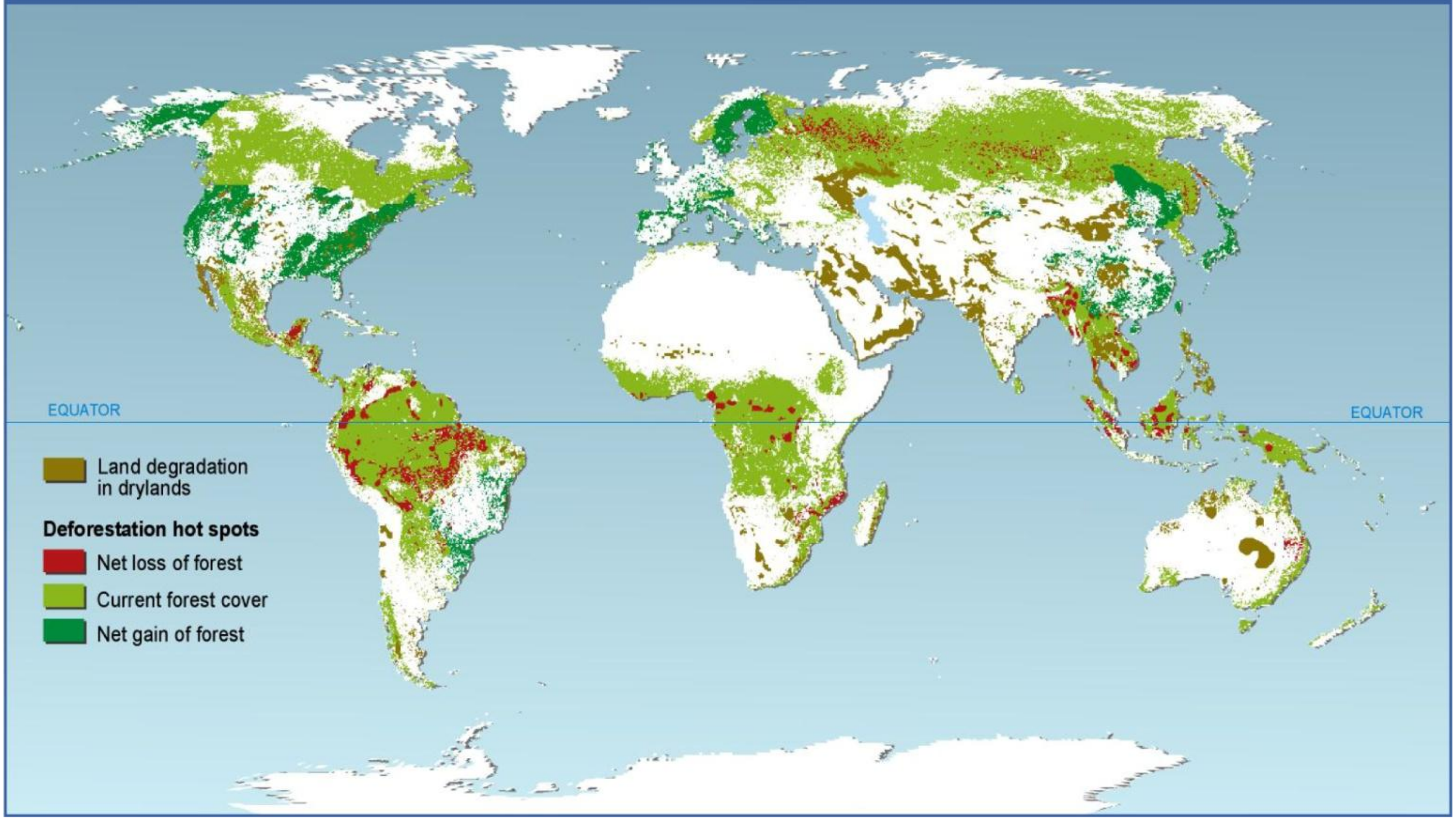
Background

- Ubiquity of "bad behavior" in physical systems
- Thresholds are routine phenomena– we've looked at much of the literature on ecological thresholds, and in some ways the greater challenge is finding a system that does not respond in this way
- But our ability to model such changes is rudimentary – yesterday, saw the example of the sensitivity of crop productivity to temperature thresholds, many other examples where there is an ecosystem threshold that is not necessarily related to an extreme in climate variability…

Background

- The major drivers of big changes over the past half-century in both managed and unmanaged ecosystems are in fact human-driven
- Land-cover changes as just one example
- We need to be able to take these sort of changes into account; heard this point made in a very interesting talk on forests this morning

Forest Cover and Land Degradation Change from 1980-2000

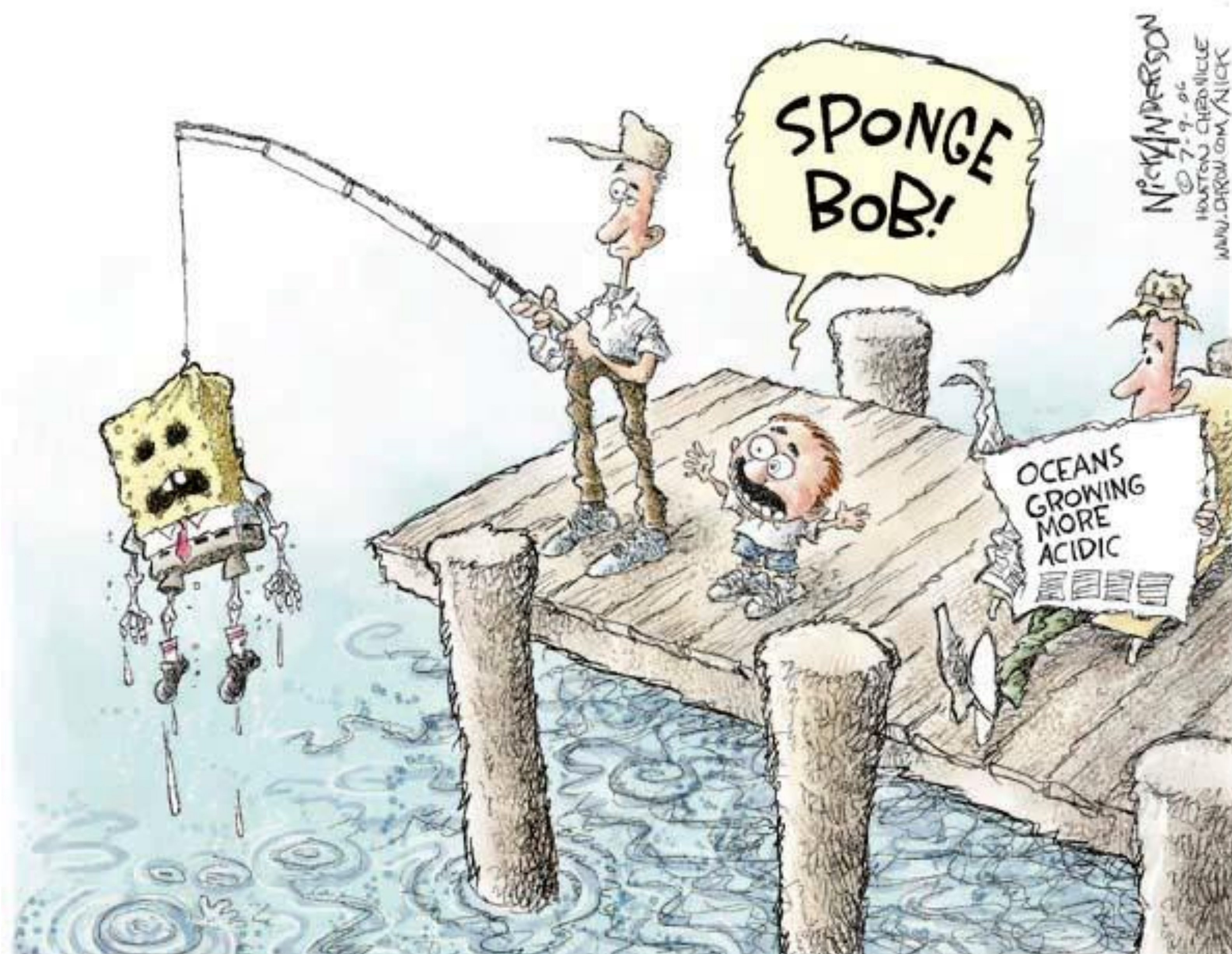


Background

- Interaction among sectors is clearly a first-order problem, not a second-order problem as we have typically treated it in impact assessments
- Competition for water among agricultural, energy, industrial and other human uses – and ecosystem uses/needs is just the tip of the iceberg
- Competition for land among economically productive uses (e.g. agriculture, forestry), provision of ecosystem services that are not valued in markets, provision of services that are not currently valued in markets, but could be in different policy regimes
- Aggregation/disaggregation issues turn out to be extremely important, and this is a challenge for the response-surface approach

Background

- Many of the ecological models that are being used have well-known deficiencies that are not being taken into account
  - They do a quite poor job of parameterizing the CO_2-driven increases in water-use efficiency, for example
  - They typically do not include the type of threshold responses mentioned before
  - They underplay or don't include biotic interactions like pests and pathogens
  - Some, including the DGVM's, are essentially unverified, and how they could be verified is not all that clear
- Some of the potential ecological changes are still in the category of being theoretically possible, but our techniques for projecting them are very preliminary (e.g. extinction risk, climate envelope modeling for range shifts)


SPONGE BOB!
OCEANS GROWING MORE ACIDIC

Background

- The technique of inferring or developing simple, statistically- or model-based response functions for use in reduced form IAMs faces some very difficult challenges
- My personal conclusion is that these techniques have utility for understanding some of the interactions of climate impacts and economic concerns in today's world – AND THIS IS REALLY IMPORTANT TO DO!
- But their ability to do projections that are intrinsically far beyond the range in which the original parameterizations and damage functions have been developed is likely to be quite limited
- My second conclusion is that a more process-based approach to linking concerns about impacts with their economic consequences and with the economic and technological evolution of both the impact sectors and climate policy is more likely to be helpful at the end of the day
- But such research also must be humbly done – with careful attention to how well we know the underlying processes, and extensive exploration of where the uncertainties are…

Some Thoughts on the Value Added from a New Round of Climate Change Damage Estimates

Gary Yohe[a c] and Chris Hope[b]

EPA/DOE Workshop on Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis: Research on Climate Change Impacts and Associated Economic Damages

January 28, 2011

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The organizers of the workshop on "Research on Climate Change Impacts and Associated Economic Damages" asked us (among others) to reflect briefly on three summary questions. The first focused on improving reduced-form integrated assessment models. The second asked for an assessment of recent progress with particular attention paid to interactions across sectors. The third invited us to identify important gaps and uncertainties. We will not attempt to answer any of these questions comprehensively. We will, though, offer some hopefully provocative thoughts that address the content of each of them, taken in turn, from a value-added perspective. In doing so, we hope to speak to the issues raised by the broader title of the two-day meeting: "Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis".

Our first set of comments expresses some concern about the value of specific contributions to integrated assessments and their products. To that end, Section 1 offers a warning to beware of analyses that are so narrow that they miss good deal of the important economic ramifications of the full suite of manifestations of climate change; i.e., they miss interactions in the climate system that allow climate change, itself, to be a source of multiple stress even within one particular sector. Section 1 also makes the point that the largest value added by updated economic analyses of impacts may be found in using their results to identify where more careful consideration of site-specific and path dependent adaptation might be most productive.

Our second set of comments focuses attention on one of the most visible products of integrated assessment modeling – estimates of the social cost of carbon which we take as one example of aggregate economic indicators that have been designed to summarize climate risk in policy deliberations. Our point, argued in Section 2, will be that these estimates are so sensitive to a wide range of parameters that improved understanding of economic damages across many (if not all) climate sensitive sectors may offer only limited value added. Some of these parameters reflect interactions across sectors. Others fall within the prerogative of decision-makers who use the results of integrated assessment to judge the value of mitigation policy. Still others fall within the prerogative of "Mother Nature"; and we must humbly admit that she is not being particularly forthcoming in providing information from which we can glean reliable and timely estimates. We fear, in other words, that the very focus of this workshop may have been guilty of a "type-three error" – that is, in the words of Richard Tol, "barking up the wrong tree".

Having cast some doubt on the ability of improved estimates of economic damages to increase the value of economic damage estimates in integrated assessment modeling designed to inform climate policy deliberations, we offer an alternative approach in Section 3. We begin with the idea that climate policy can perhaps best be understood as a question of setting a carbon-emissions budget for a period of decades rather than centuries – say limiting cumulative emission from the United States to between 170 to 200 gigatons through 2050 as suggested in the report of the "Limiting Panel" to America's Climate Choices [NAS (2010)]. Working from there to suggest how to set a price on carbon, we end this brief note by describing implicitly a research agenda that could (a) effectively inform mitigation decisions while, at the same time, (b) providing economic estimates for aggregate indicators like the social cost of carbon. It is these estimates that can be applied to considerations of the value (or harm) caused by the carbon-emission consequences of non-climate regulations and other market interventions. We believe that working out the technical and practical details of such an approach could pay the greatest dividends – an approach that would use the results of integrated assessment models to characterize policy context and judge economic tradeoffs.

Section 1: Beware of Spurious Precision and Incomplete Models.

The workshop offered glimpses into current work across a wide range of sectors and contexts, but we are worried that any single paper could be taken as comprehensive coverage of what is known and/or what needs to be known. Take, for example, the contribution by Mendelsohn, Emanuel, and Chonabayashi on tropical cyclone damage. We do not mean to pick on this paper, but it does speak to climate impacts in a sector with which we have some familiarity. The authors used historical records to calibrate simulations of future cyclones with and without climate change using a collection of 4 global circulation models along the A1b SRES storyline. Based on statistical associations of storm intensity and observed damages, they conclude that "Increasing future income and population is predicted to increase annual tropical cyclone damages from $26 billion to $55 billion even with the current climate. However, damages as a fraction of GWP are expected to fall from their current rate of 0.04 percent in 2010 to 0.01 percent in 2100."

While the analysis is solid as far as it goes, we are afraid that it makes only a small contribution to our understanding of vulnerability to coastal storms that could easily be misinterpreted for two reasons. First of all, while the analysis did use four alternative climate models to simulate the future implications of 70,000 simulated cyclones, it did not provide any insight into the true range of possible damage futures. It did not, for example, explore alternative socio-economic futures (either within A1b with respect to geographical distribution of populations and development or across alternative story-lines). Nor did it explore uncertainty boundaries defined by its estimates of damage elasticities (with respect to income and population). It did not even explore uncertainty boundaries defined by any portion of the reported range of equilibrium climate sensitivity – an increasingly common feature of contemporary impacts analyses. It follows that the $26 to $55 billion *range* must be understated; it is easy to envision not-implausible economic futures for which $26 billion is too high, but it is equally easy to envision futures for which $55 billion is way too low.

The analysis also falls well short of providing comprehensive estimates of the economic damage of either tropical cyclones or coastal storms more generally. This is, in part, because it completely ignores major components of potential damage. Loss of life comes to mind in this regard; and while ignoring this risk avoids the controversy about international distributions of the value of a statistical life, it does so at the expense of severely limiting the coverage of the reported estimates.

In addition, because the analysis relies heavily on central tendencies in its statistical representation of future damages, it misses entirely the enormous inter-annual variability in cyclone damage about which insurance and re-insurance companies would be far more interested. Katrina dominates any damage time series over the past few decades in a way that is not reasonably reflected in the annual means (or medians, for that matter). Indeed, only researchers who recognize that the sheer magnitude of a Katrina-like outlier cannot be excluded from any year's potential exposure will be able to appreciate the enormous adaptation challenge that it poses. Spreading annual risk geographically may not be enough for tropical cyclones. It may be necessary to spread risk over time, as well; but to do so would require regulator reform of the sort now being suggested by Kunreuther and Useem (2010).

Mendelsohn, *et al.* also ignore the contribution of even modest sea level rise to damages associated with storms of all shapes and sizes. The authors are, in fact, completely wrong when they assert on the basis of simple statistical analysis of damages (in the text that describes the content of Figure 5) that "common small storms are not different before and after climate change." Kirshen, *et al.* (2008), Rosenzweig, *et al*. (2010), and others have argued convincingly that sea level rise elevates storm surges associated with any coastal storm and therefore amplifies any storm's potential for causing economic damage. The mechanism is really quite simple. Elevated storm surges driven by routine sea level rise can make what is now, for example, a 20-year storm look like the current 50-year storm in terms of economic exposure. In other words, what is now the 50-year storm in terms of economic consequence can turn into an every other decade (on average) event at some point – and for some locations, some time in the relatively near-term future. Table 1 offers some evidence of what this association could mean for what is currently the 100-year storm in Boston and New York along two SRES emissions trajectories and central tendency sea level rise.

Figure 1 brings this simple process (for storms of all dimensions) into geographic focus by plotting the frequency of threshold anomalies per year for 5 different locations along the north-eastern coastline of the United States from 1920 through 2005; these are locations that have experienced, on average between 2.6 cm and 2.8 cm of sea level rise per decade since 1920. The various panels of Figure 2 show what this process understanding means for an urban coastal community in Boston. Offered simply as an illustrative example, it shows damage profiles (without adaptation) at 20-year increments that were drawn randomly from probabilistic representations of historical weather patterns (without altering intensity or frequency in anticipation of climate change). This historical pattern was then superimposed upon sea level trajectories that reach 100 cm and 60 cm by 2100.

Notice that damages from the worst 5% of the storms (including, perhaps, an occasional representation of a hurricane or a severe winter nor-easter with hurricane force winds) are expected to climb over the century by as much as 250% (along the 100 cm trajectory); this is flooding analog to what Mendelsohn, *et al*. estimate as a function of storm intensity that is implied by the first rows of Table 1. More importantly, notice that damages from the other 95% of the storms are expected to increase similarly and persistently over time at rates that are determined by the underlying sea level rise scenario.

Clearly, these risk profiles show that common storms *can be quite different under climate change when the local characteristics of climate change are more comprehensively represented*; and clearly, those differences can produce some relatively large economic consequences. These sorts of risk profiles can also help decision-makers decide how and when to respond to a growing climate-related risk. Table 2, for example, charts the increase in the estimated expected internal rate of return for an investment in protective infrastructure that would (a) cost $390 million (in real dollars) to implement, (b) commit the city to 10% maintenance expenses thereafter, and (c) not guarantee complete protection from the upper end of the damage distribution. These *economic* estimates show that the need for adaptation could be urgent (or not), depending on the degree to which this public investment would complement private investment [see, e.g., Ogura and Yohe (1977)] and the speed with which sea level are seen to be rising rise.

Section 2: Value Added for Aggregate Economic Indicators like the Social Cost of Carbon.

Downing and Watkiss (2003) warned that economic analyses of climate change damages failed to cover much of what might be in store for the planet (especially in terms of socially contingent consequences and abrupt events). While little has changed to allay their concerns, this section will not rehash their arguments. It will, instead, ask (and, to some degree, answer) a simple question: "What difference would marginal contributions to economic damage estimates (for the impacts and sectors that we can model) make on the major economic aggregates that some believe most significantly inform climate policy deliberations?" We know that uncertainty compounds through the climate system as we move from (a) economic activity to (b) greenhouse gas emissions to (c) changes in their atmospheric concentrations to (d) changes in global mean temperature and other climate variables to (e) impacts in physical and biological systems to *(f) economic estimates of associated damages with and without adaptation.* Since new estimates of economic damages speak only to the last (italicized) association, it would seem fool-hearty not to hypothesize that the answer to this question is "Not much!"

To begin to explore the potential validity of this hypothesis, we used the latest version of the PAGE integrated assessment model (PAGE 09) to track the implications of three possible implications of a new round economic damage estimates (of the sort presented at the workshop) on the distribution of estimates of the social cost of carbon.[1] The baseline scenarios worked from a representation of the SRES A1B storyline whose default settings produced the range of temperature trajectories depicted in Figure 3. The three experimental changes from the default settings were designed to reflect improved (or at least altered) understanding of economic damages across the board. Results (calibrated in terms of the social cost of carbon) from the default-setting baseline and three experiments are recorded in Table 3 and depicted graphically in Figure 4. In every case, the summary statistics of Table 3 and the histograms of Figure 4 were produced from monte carlo simulations that involved 100,000 distinct manifestations of the complete set of underlying random

[1] See Hope (2006) for details of the structure of the PAGE models. For updates included in PAGE09, see http://climatecost.cc/images/Policy_brief_4_PAGE09_Model_vs_2_watermark.pdf.

variables that PAGE 09 can accommodate.

In the first experiment (Case A in Table 3), new economic research was assumed to reduce the range of the parameters that calibrates estimates for economic sectors and coastal zones by 50% without changing their means or the modes. In the second experiment (Case B), new research was assumed to reduce the modes by 50%. Since the distributions of all parameters are triangular in PAGE 09, reducing the mode by 50% reduces the mean by almost 9% and puts an additional 17% of the probabilistic density below the old mean. This might not seem like much from a modeling perspective, but we submit that it reflects what would be a gigantic change against conventional wisdom that is anchored by the inertia of decades of earlier research. The third experiment (Case C in Table 3) repeats Case B in the opposite direction; i.e., the mode is increased by 50%.

Given that these results are based on 100,000 runs, there is a 95% chance that another set of 100,000 runs would produce means in every case that are within $2 of these reported values. The summary statistics therefore strongly suggest that it would be unlikely that reducing the range of economic damage estimates would change the mean estimate for the social cost of carbon even though the 99th percentile estimate might fall by more than 10%. Cases B and C, where the mode changed, did show significant changes in the mean and slight changes in the 5th to 95th percentile ranges; but these changes are nothing to write home about in terms of making policy. Indeed, the histograms portrayed in Figure 4 depict vivid portraits of robust i*nsensitivity* to new information about economics. Estimates range from $0 through nearly $10,000 or more per ton in every case, but the modal estimates all lie between $25 and $50 per, the median estimates all fall in the neighborhood of $50 per ton, and the means (excluding the top 1% of the estimates) all hover between $80 and $90 per ton (adding the top 1% of the estimates would add roughly $20 to these values).

The relative insensitivity of these statistical values is supported by analysis of the marginal contributions of uncertainty in the underlying random variables to the overall variability in estimates of the social cost of carbon. Transient climate response dominated for every case, followed (among sources reflecting human attitudes or activities) by the pure rate of time preference (about 60% as influential and transient sensitivity), relative risk or inequity aversion (about 50% as influential), indirect effects of sulfates (about 25% as influential), and non-economic effects (also about 25% as influential). The influence of the exponent coefficient for economic damages lies below all of these and some others – roughly one-eighth as influential in determining the range of estimates in the social cost of carbon as transient climate sensitivity.

The various panels of Figure 5 display the actual correlation estimates. They show, for example, that increasing transient climate response parameter (TCR) by 1 standard deviation above its mean in the default case would increase the social cost of carbon by $67 while doing the same for the economic damages parameter (POW-1) would increase the social cost of carbon by only $9. Similar disparity is clearly apparent for the other three cases. Put another way, any change in economic estimates of damages that new literature might produce is easily undone by small adjustments in other parameters and/or purposeful adjustments in judgmental parameters (e.g., time preference or risk and inequity aversion).

The numerical results reported here are, to be sure, highly model-specific both with respect to the sources of uncertainty that are represented explicitly in its structure and the way those sources are depicted. Other models may suggest that dramatic change in the overall distributions of economic damages might be more (or less) influential in determining the social cost of carbon, but we do not think that the qualitative conclusion that they illustrate. We do not think, in other words, that our hypothesis of minimal value added is right would be weakened substantially if other models were similarly exercised.

Section 3: Barking up a Different Tree for Value Added.

To us, at least, it follows from the hypothesis that we raises and supported in Section 2 that economic aggregates should not be the (sole) foundation upon which to build climate policy. They can, at best, contribute to an understanding of context within which policy alternatives derived from other sources should be evaluated. That is to say, they can contribute to analyses of whether or not those alternatives can achieve their stated climate objectives at least cost and, in some cases, whether or not they might be doing more harm than good. There is, after all, such a thing as dangerous climate policy; see, for example Tol and Yohe (2007). In addition, the more detailed modules from which these aggregates are constructed can help decision-makers and researchers alike identify where careful consideration of an expanded set of adaptation options might be most productive. Nonetheless, we fear that trying to devise a way to set the price of carbon (or the economic value of emissions reductions or increases from a non-climate policy, for that matter) equal to something like the social cost of carbon is probably a fruitless enterprise. Moreover, justifying impacts analyses completely on the basis of improving the quality of their contributions to estimates of the social cost of carbon is likely to be a misguided enterprise.

So what should we be doing, instead? The authors of the report of the Limiting Panel to America's Climate Choices [NAS (2010)] offered what we view to be a solid suggestion. They recommended a multi-step process that would begin with assessing a wide range of climate risks that will materialize over the medium to long-term. They recognized that these risks will be calibrated in many monetary and non-monetary metrics and that it will be up to the political process to determine a socially acceptable level of risk. Given that determination, it should be possible to identify long-term mitigation targets in terms of temperature increases and associated ranges of atmospheric concentrations; and from there, it should be possible (a) to deduce a medium-term global carbon emissions budget that would put the planet on a path from which iterative decisions based on new climate science and technological development could be designed and implemented effectively and (b) infer the United States (and other country, for that matter) contributions to that budget.

Each of the steps noted above can, of course, be identified as a research topic, particularly the iterative component of evolving long-term policy objectives and medium-term carbon budget targets. Several researchable topics come to mind almost immediately. What should be monitored to inform iterative decisions, for example? How should "mid-course" corrections be implemented, and what types of institutions need to be created to make them maximally efficient? And how frequently should they be undertaken?

More to the point of this workshop, though, how could a medium-term carbon budget target be achieved? NAS (2010) concluded that it is necessary (but not sufficient by any means) to set a price on carbon that increases predictably and persistently over the applicable time period. Since even a medium-term emissions budget can be viewed as an inter-temporal exhaustible resource problem, the first-order answer to how to price carbon comes straight from Hotelling (1931): compute the scarcity rent for year one and let it increase over time at the rate of interest. The actual best trajectory will depend, of course, on the rate of growth in economic activity, the rate of technological innovation in non-carbon intensive energy sources and carbon sequestration, and other factors that cannot be predicted accurately for 40 year time periods; but these insight highlights yet another set of researchable questions about quantification and short-term term iteration processes. Perhaps the most practical approach would involve identifying technologies that could contribute most to emissions reductions and evaluating the cost of carbon that would be required to make them economically competitive with fossil-base alternatives at the time they would become viable. As described in Yohe, *et al* (2007), the appropriate initial scarcity rent could, quite simply, be the level that would, if it were to climb at the rate of interest, reach the pricing threshold at just the right time; but this, too, is a researchable issue.

And what role can damage estimates play in all of this? It seems to us, as noted above, that they provide context in a very important sense. Ranges of aggregates like the social cost of carbon offer fundamental access to the answers of questions like "What combinations of normative and scientifically-based parameters produce discounted marginal damage estimates that are consistent with carbon pricing proposals born of technological modeling and national carbon emissions budgets? And are those combinations consistent with the normative view of how the world should behave from which the long-term objectives and medium-term targets were derived?" Their content, in other words, is not numerical; it is, instead interrogatory.

Section 4: A Concluding Thought.

Answers to the research questions identified in Section 3 that were informed directly by our brief comments in Sections 1 and 2 would not be unique, of course, and that complication must be acknowledged from the start. So, too, should the pervasive uncertainties that will not, in many cases, be resolved in a timely fashion. We close, therefore, with a reference to a lesson articulated almost two decades ago by Lester Lave – an economist of considerable note and wide experience in climate-related issues who worked for decades at Carnegie Mellon University in Pittsburgh. He once told the then fledgling Center for the Study of the Human Dimensions of Global Environmental Change that "If it does not make a difference of a factor of two, then it is inside the noise. With that fact of life we will simply have to learn to cope." Correcting for misrepresenting trends inside that noise is, quite fundamentally, why iteration is so essential in all of this – it is the first order question that must be confronted directly if we are to have any success in *Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis*.

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Table 1. Estimated Storm Surge Elevations and Return Times of the Current 100-year Storm Anomalies for Boston and New York. Estimates based on median sea level rise scenarios for the B1 and A1FI SRES scenarios with historical pace of local sea level rise indicated in parentheses. Source: Kirshen, *et al.* (2008).

	Storm Surge Elevation			Recurrence of 2005 100 yr Storm	
Location	**2005**	**2050**	**2100**	**2050**	**2100**
Boston (2.65 mm/yr; 1921-2005)					
B1	2.9 m	3.0 m	3.1 m	15 yr	5 yr
A1FI	2.9 m	3.2 m	3.8 m	3 yr	<< 2 yr
New York (2.77 mm/yr; 1920-2005)					
B1	2.8 m	2.9 m	3.0 m	50 yr	30 yr
A1FI	2.8 m	3.1 m	3.7 m	30 yr	3 yr

Table 2. Estimated Internal Rates of Return for Investment in Protective Infrastructure over Time: Estimates of the expected internal rates of return for investing in a $390 million (real terms) protective infrastructure against the increasing economic risk driven by climate change and portrayed in Figure 1 for an urban area in Boston. Source: Yohe, *et al.* (2010)

Year	1 meter SLR(2100)	0.6 meter SLR(2100)
2010	2.1%	-0.5%
2015	3.8%	0.2%
2020	4.3%	0.4%
2025	5.2%	0.8%
2030	6.4%	1.3%
2035	8.4%	1.8%
2040	12.4%	2.5%
2045		3.4%
2050		5.0%

Table 3: Summary Results for the Social Cost of Carbon (per ton of CO_2): Summary results from 100,000 runs for the default settings are compared with cases in which (Case A) the range of economic damages in general and attributed to sea level rise shrinks by 50%, (Case B) the ranges of both stay the same but the modes shrink by 50%, and (Case C) the ranges of both stay the same but the modes increase by 50%. Schematics of the critical distributions are provided for each.

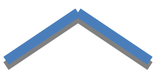
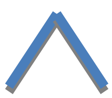
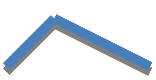
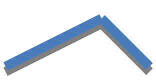
Case	Min	5th	Mean	95th	99th	Max	Mean of Lower 99%	Contribution of Top 1% to Mean
Default	-$4	$12	$106	$259	$1191	$12215	$85	20%
	*Symmetric default settings for the economic damage and sea level rise calibrations*							
Case A	-$1	$12	$106	$258	$1168	$10084	$85	20%
	*Ranges for the two economic damage parameters diminished by 50%*							
Case B	-$2	$10	$102	$248	$1108	$9131	$80	22%
	*Ranges preserved but distribution skewed with the mode 50% lower*							
Case C	-$3	$13	$111	$272	$1218	$13166	$89	20%
	*Ranges preserved but distributions skewed with the mode 50% higher*							

Figure 1: Observed Frequencies of "Over-threshold" Events in Select Locations along the Northeastern Coastline of the United States since 1920: The number of "points-over-threshold (POT) anomalies per year for each site; a strongly increasing trend in the number of POT anomalies was detected at all sites. Source: Kirshen, *et al.* (2008).

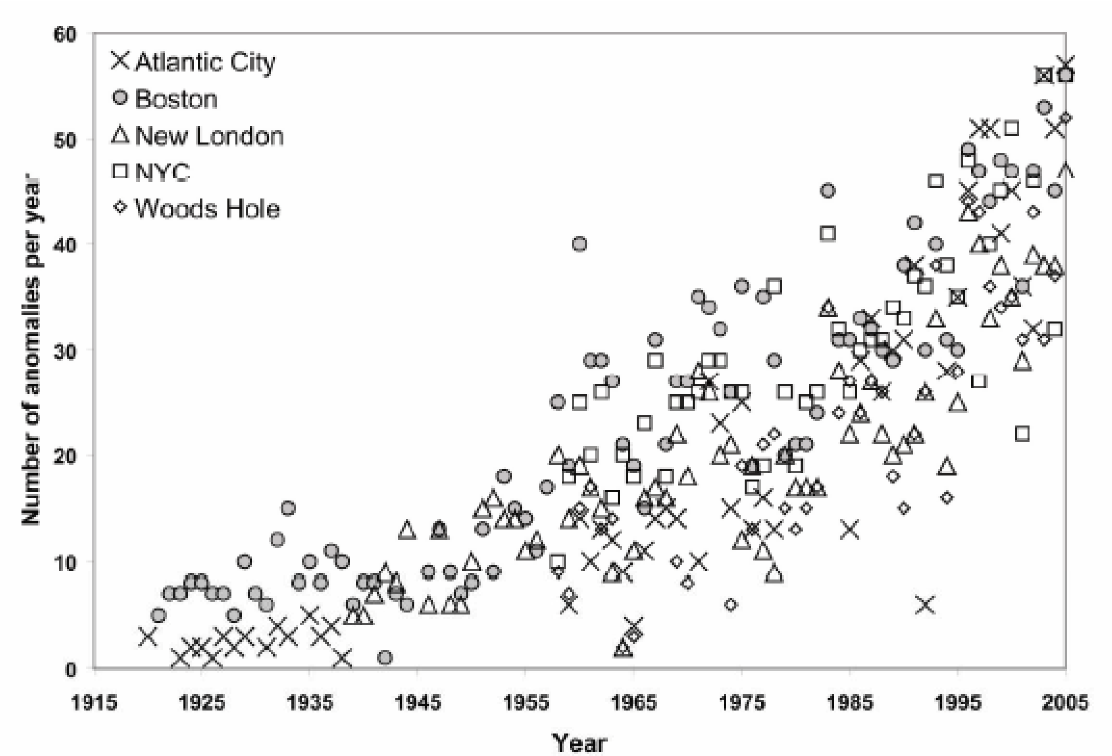
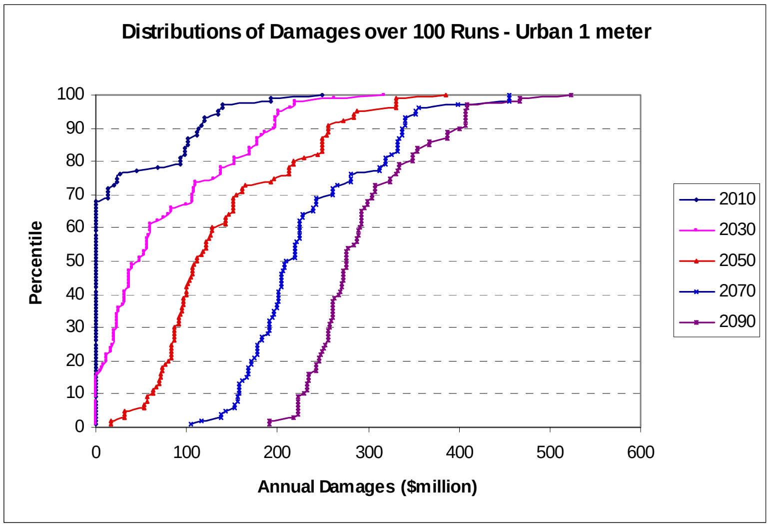
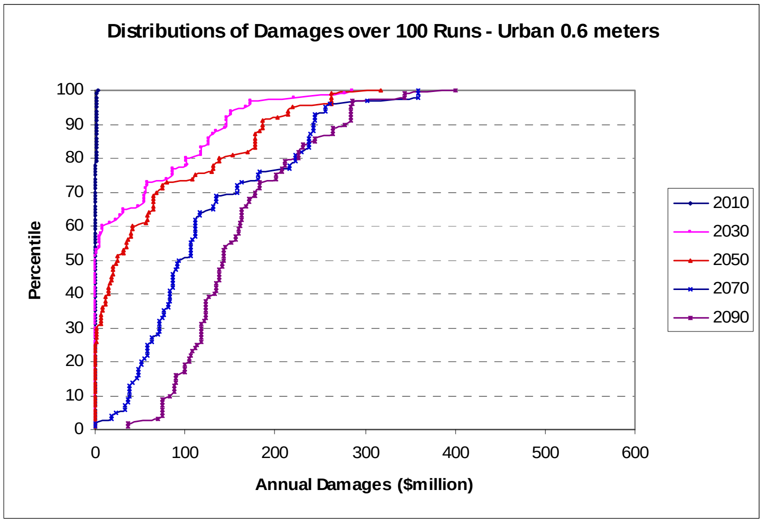


Figure 2: Damage Profiles from Coastal Storms over Time for Two Sea Level Rise Trajectories: Distributions of economic damage across 100 runs for two sea level rise scenarios. Panels A and B indicate economic damages from coastal flooding in selected years in the future for an urban area in Boston along 1.0 and 0.6 m sea level rise scenarios, respectively. These estimates do not include adaptation. Source: Yohe, *et al.* (2010)



Panel A



Panel B

Figure 3: Global Mean Temperature (relative to pre-industrial levels): The thick middle line represents the mean for an A1b-style story-line with default settings. 75th and 95th percentiles runs for the 100,000 permutations run above the mean; 25th and 5th percentile trajectories run below.

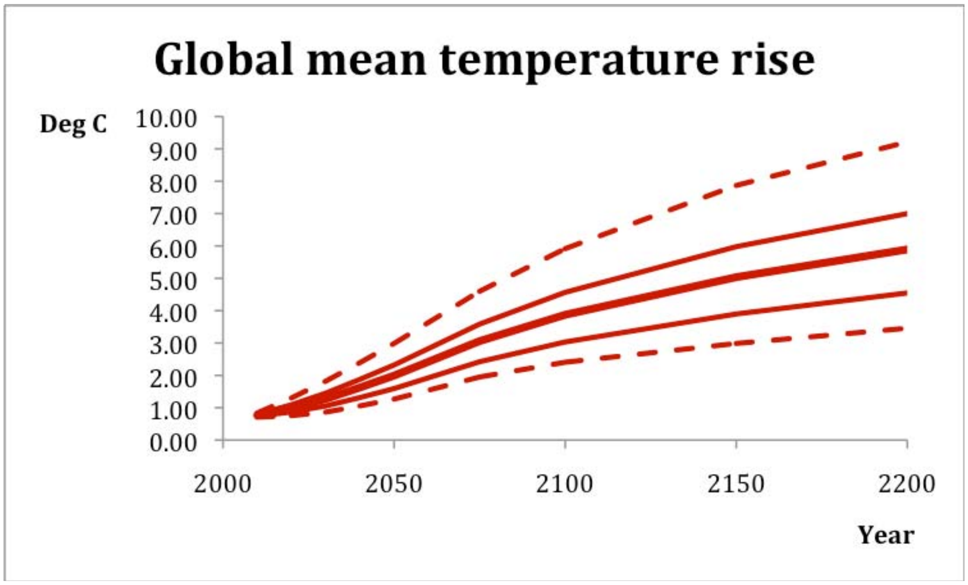
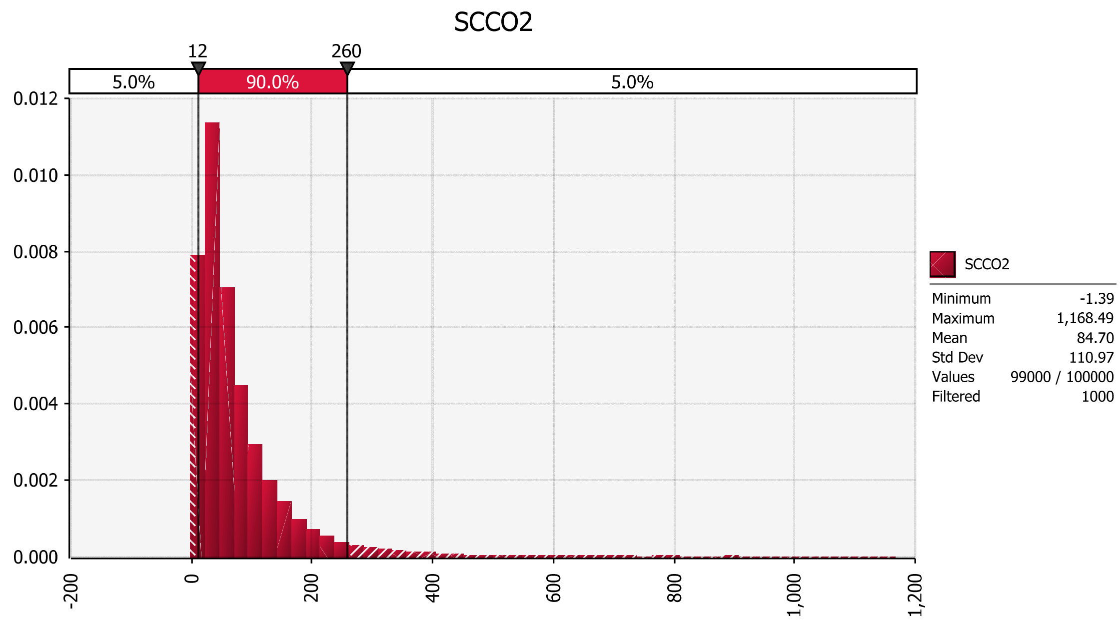
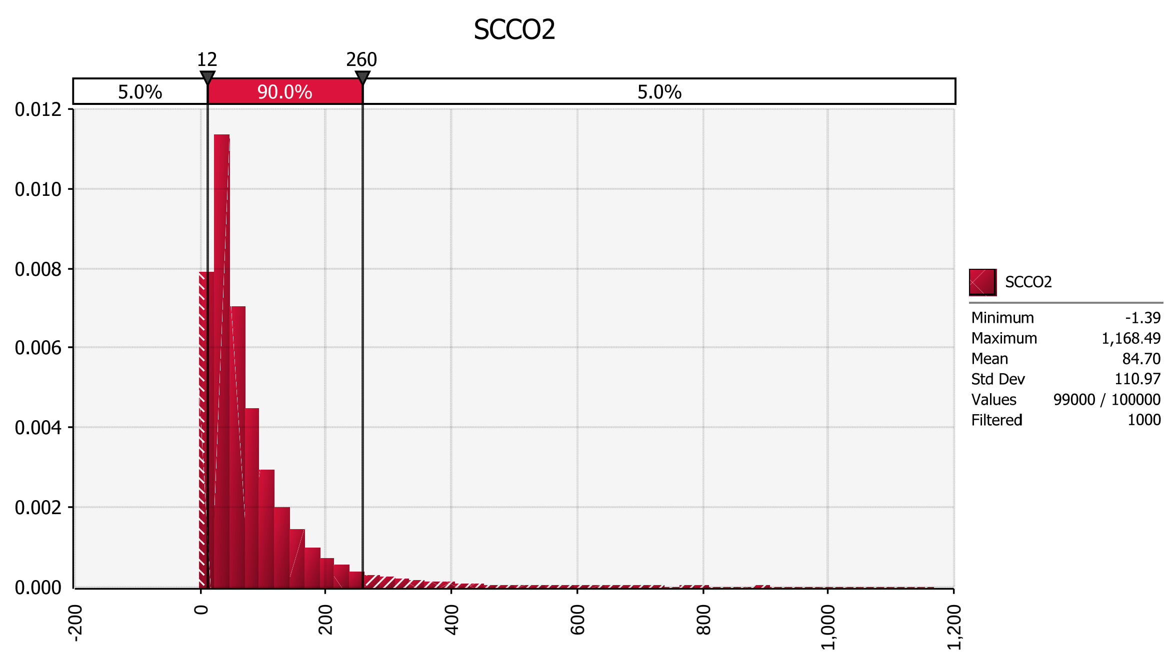


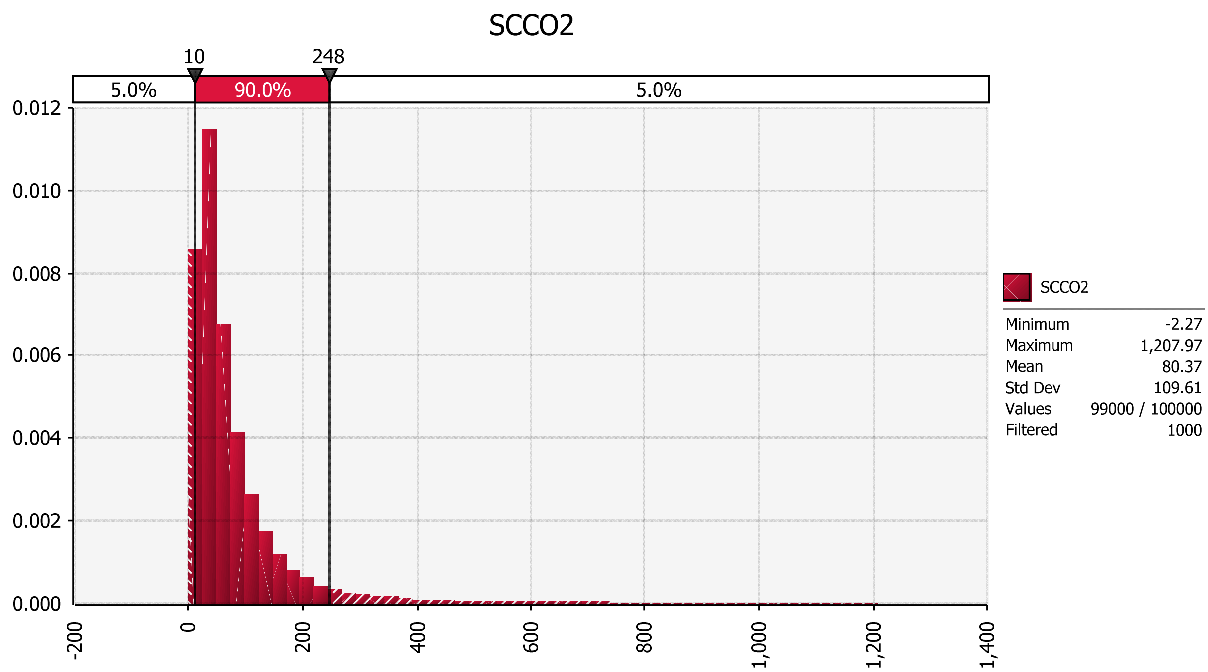
Figure 4: Histograms of the Social Cost of Carbon. Distributions of estimates of the social cost of carbon from 100,000 randomly selected futures (excluding the upper 1% of the estimates so that the shapes become clear). Panel A depicts the default baseline. Panel B depicts Case A – reduction in the range of the parameters that calibrates estimates for economic sectors and coastal zones by 50% without changing their means or the modes. Panel C depicts Case B – 50% reductions in the modes of those parameters without changing their ranges. Panel D depicts Case C – 50% exaggeration of the modes of those parameters without changing their ranges.



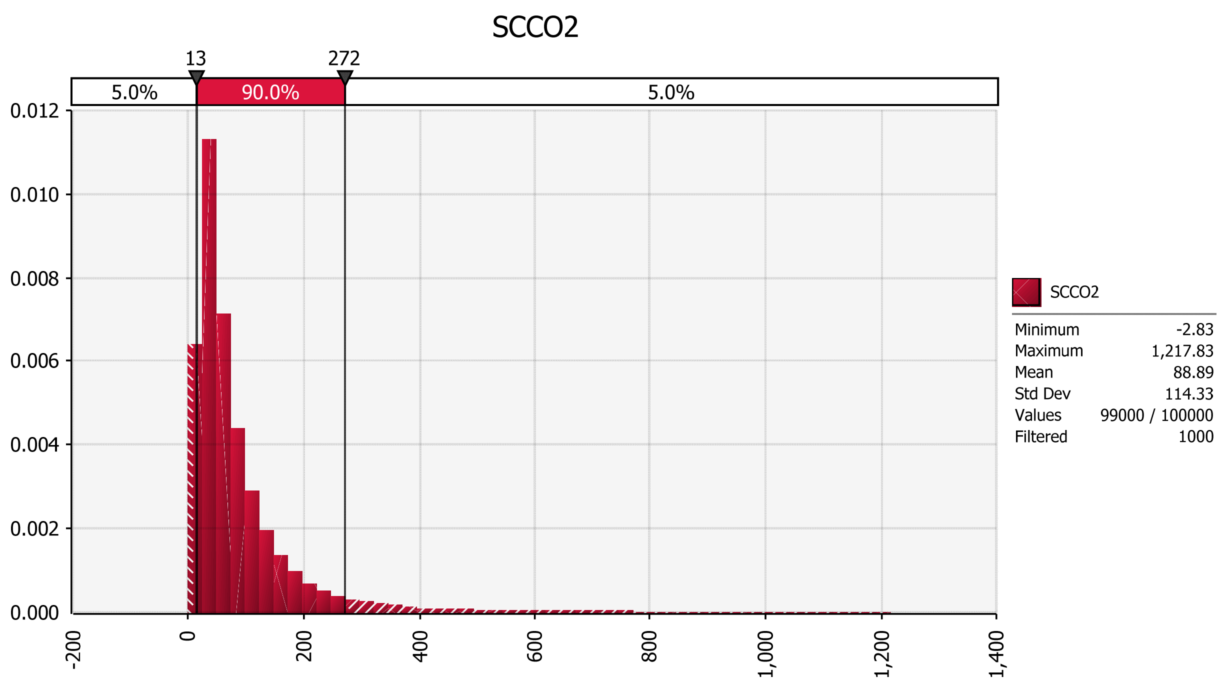
Panel A



Panel B

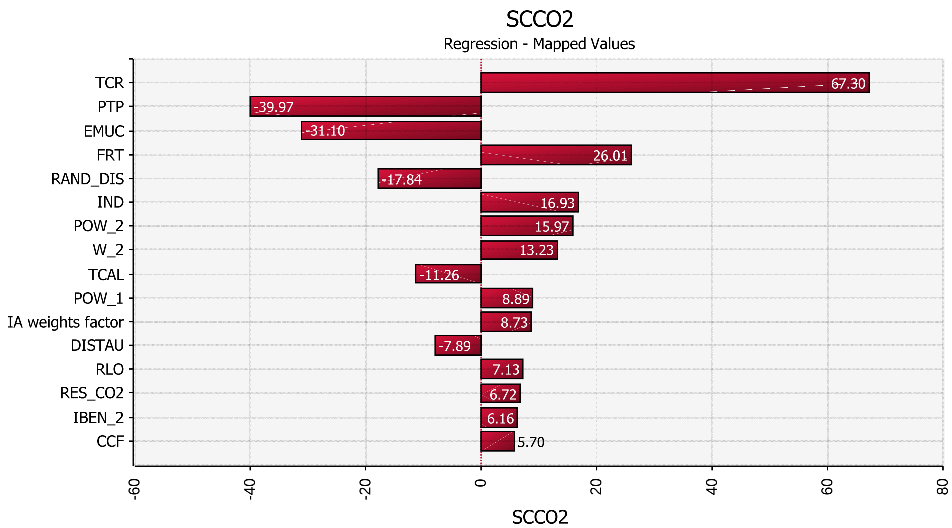


Panel C

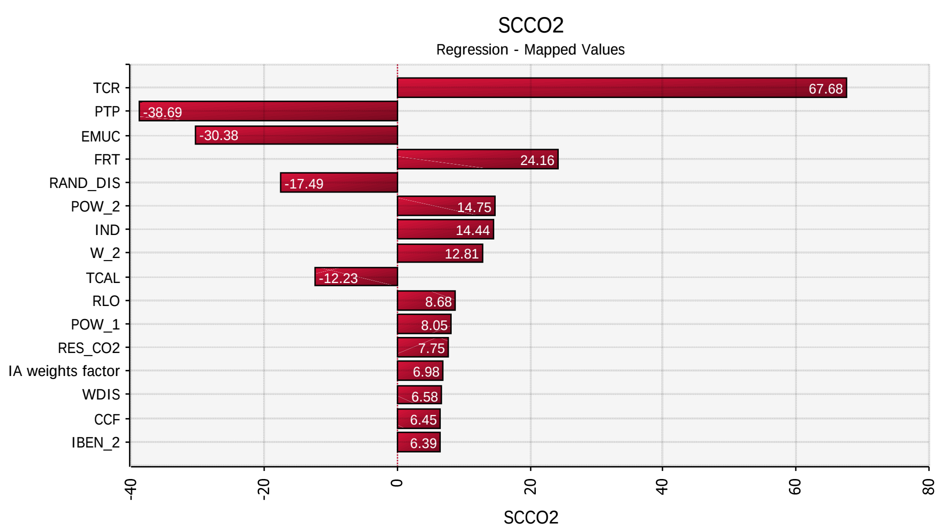


Panel D

Figure 5: Marginal Contributions of Various Parameters to Variability in Estimates of the Social Cost of Carbon. The bars indicate the direction and strength of various parameters in sustaining variability in estimates of the social cost of carbon; cases are as defined in Figure 4.[2] The value of 67 assigned to transient climate response (TCR) indicates, for example, that increasing TCR by 1 standard deviation above its mean would increase the social cost of carbon by $67. Increasing the economic damages parameter (POW-1) by 1 standard deviation would, by way of contrast, increase the social cost of carbon by only $9.

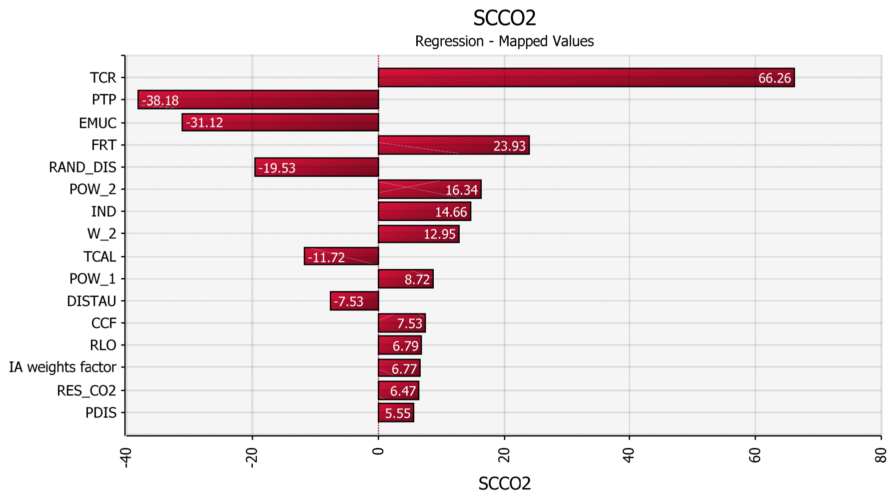


Panel A

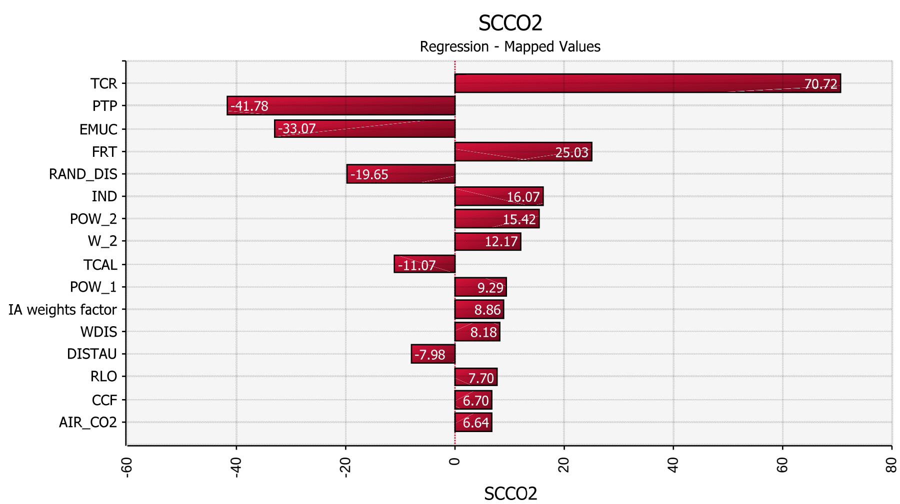


Panel B

[2] Partial Glossary: TCR – transient climate response; PTP – pure time preference rate; EMUC – (negative of the) elasticity of the marginal utility of consumption; FRT – feedback response time; IND – indirect effect of sulfates; POW-2 – exponent of the non-economic impact function; W_2 – non-economic impact at calibration temperature; TCAL – calibration temperature; POW-1 – exponent of the economic impact function.



Panel C



Panel D

Some Thoughts on the Value Added from a New Round of Climate Change Damage Estimates

Gary Yohe[a c] and Chris Hope[b]

EPA/DOE Workshop on Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis: Research on Climate Change Impacts and Associated Economic Damages

January 28, 2011

Outline of Brief Remarks

- More complete paper available.
- *Section 1 – Issues with Coastal Storms.*
- Section 2 – Type 3 Error – Barking up the wrong tree means very little value added.
- Section 3 – There is an alternative – the Limiting Panel plus iteration – here is value added for an aggressive research agenda.
- Economic analyses of impacts help ID places where adaptation would be important; “laugh test context for the alternative.

Experiment Results - SCC

Case	Min	5th	Mean	95th	99th	Max	Mean of Lower 99%	Contribution of Top 1% to Mean
Default	-$4	$12	$106	$259	$1191	$12215	$85	20%
	*Symmetric default settings for the economic damage and sea level rise calibrations*							
Case A	-$1	$12	$106	$258	$1168	$10084	$85	20%
	*Ranges for the two economic damage parameters diminished by 50%*							
Case B	-$2	$10	$102	$248	$1108	$9131	$80	22%
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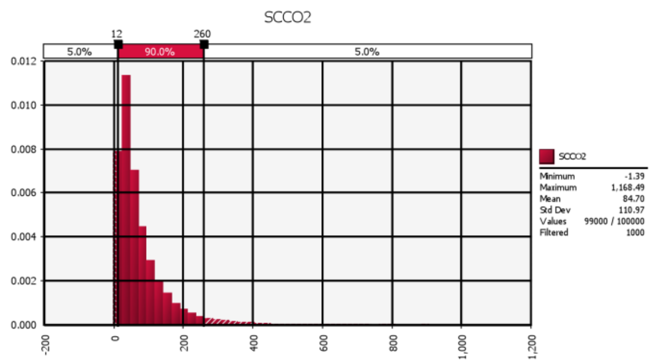
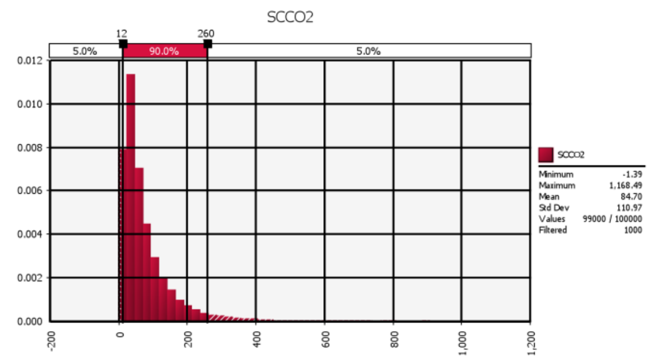
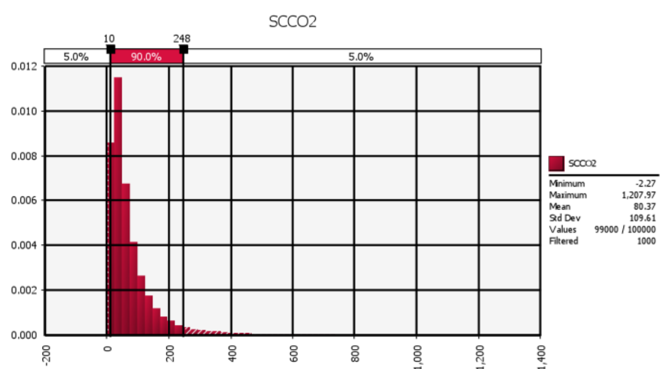
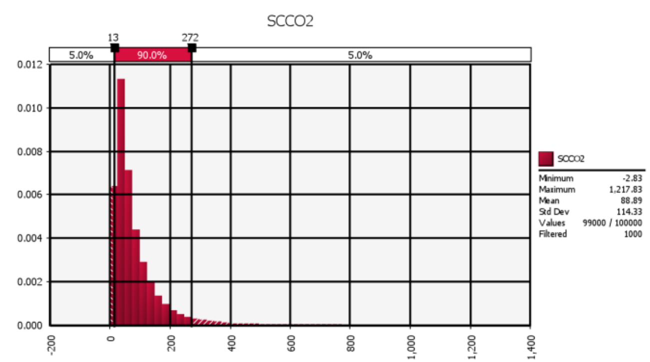
Experiment Results - SCC





- Panel A – Default Panel B – Reduced Range





- Panel C – Mode 50% Lower Panel D – Mode 50% Higher

An Alternative Approach – A Different Tree for Barking with higher Value Added

- Use assessment of climate risk to determine long-term objective and medium-term carbon budget – *build the iterative process*
- Work within the process to determine US contribution to the budget
- *Compute scarcity rent trajectory for the budget (a la Hotelling) and then add details of economic growth, technological development, etc… build the iterative process.*
- Use the results to price carbon for non-climate policy needs
- Use IAM results to (1) check the "laugh test", (2) design cost-minimizing approaches (including net economic damage) and (3) highlight areas where adaptation in economic sectors will be most productive.